THE UNIVERSITY OF ALBERTA

THE EFFECTS OF UPPER-LEVEL WINDS AND TEMPERATURES ON THE PROBABILITY OF HAIL IN CENTRAL ALBERTA

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "THE EFFECTS OF UPPER-LEVEL WINDS AND TEMPERATURES ON THE PROBABILITY OF HAIL IN CENTRAL ALBERTA," submitted by MICHAEL C. GOW in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The relationships between winds and temperatures at the surface, and at upper-levels, and the probability of hailfall have been investigated by a number of workers in the field of severe weather forecasting. Using hailfall data from the Alberta Hail Studies project and upper-air data from the Calgary and Edmonton radiosondes, this thesis attempts to confirm the validity for use in Alberta, of a number of previously developed hail-forecasting techniques and to suggest a number of new techniques that may merit operational testing. A hail index that takes into account the size distribution of hail on a particular day is also suggested.

ACKNOWLEDGEMENTS

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During the summer of 1967, I worked with the Alberta Hail Studies group at Penhold. I obtained a great deal of help from members of the hail studies staff, and became familiar with the problems of hail forecasting. In particular I would like to thank Dr. Peter Summers, the head of the Alberta Hail Studies field program, and Mr. James Renick, his assistant, for their valuable advice and assistance.

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CHAPTER I

INTRODUCTION

Hailfall Climatology

The distribution of hailfall has been under detailed observation for only about twenty years, and, for the most part, only in areas of severe hailstorm acitivity. There are, however, reports of severe hail activity dating back to Biblical times (The Book of Joshua). With the advent of a surface weather reporting network in the United States in about 1860, it became possible to obtain some idea of the distribution of hailstorms on a regional basis.

In the tropics, hail is a relatively infrequent phenomenon. This is the result, for the most part, of the higher altitude of the freezing level in lower latitudes than in mid-latitude regions. As a result of these higher freezing levels, convectional processes must be present which are intense enough to produce clouds with tops extending to these greater heights so that the freezing processes required for hail formation can take place (Frisby and Sansom, 1966; Flora, 1956). When these convectional processes are present, it is probable that a hailstone formed in the cloud will melt before reaching the ground. The hailstone melts because of the great

depth of above-freezing air through which it must fall. The point frequency of hail in the tropics is generally found to be less than two days per annum, except in mountainous regions such as the highlands of Kenya where frequencies of from five to ten are not uncommon. This increased hail frequency in mountainous areas is the result of the effect of orographic lift in promoting convection to sufficient heights for hail production, and to the shallower depth of above-freezing air at higher altitudes than at lower ones. This is not to say that such phenomena as the inter-tropical convergence zone are not responsible for many of the severe hailstorms in the tropics. Hurricanes, especially, are frequently accompanied by severe local hailstorms.

In mid-latitudes, hail occurs more frequently than in the tropics. Because of this, mid-latitude hail has been under closer observation for a longer period of time than in other parts of the world. In North America, the Great Plains of the United States and the southern sections of the Prairie Provinces of Canada have point hail frequencies considerably greater than those which are representative of other mid-latitude regions. Many North American hailstorms develop in the lee of the Rocky Mountains, and as a result many hail research projects have been located in this area. This phenomenon of hailstorm breeding zones being on the lee side of extensive mountain ranges is found in many

other parts of the world, such as New Zealand, the Caucusus region of the U.S.S.R. and Italy (Powell, 1961). The ratio of days with hail to days with thunderstorms is an interesting quantity. The ratio varies from 0.02 in the Gulf States, to 0.10 in the Great Plains, to 1.00 on the Pacific Coast (Flora, 1956). The high value on the Pacific Coast is caused by the prevalence in this region of soft hail, which sometimes falls in non-thunderstorm situations. The ratio has been found to be 0.20 in southern Alberta and 0.11 in north-central Alberta (Powell, 1961).

Although the development of a synoptic reporting network provides a good picture of hail distribution on a scale of the order of hundreds of miles, it is necessary, in order to study hailfall in detail, to have a reporting network with a density of at least one observer per twenty-five square miles. This is necessary because of the limited extent, both in width and length, of the swath of a hailstorm. In North America, there have been a number of projects set up to observe hailfall on this scale.

(i) The Denver Network

This was set up in 1949 to investigate hailstorms in the Denver area, as a result of concern by United Airlines for the safety of their aircraft which had many times sustained damage from hailstones in this region (Beckwith, 1960). Since 1951, they have had a reporting

network of fifty stations in an area of about one hundred and fifty square miles.

(ii) The Colorado State University Network

This project's area covers approximately sixty-five hundred square miles in eastern Colorado (Schleusener and Grant, 1961). Beginning in 1960, information on hail days, storm track directions (augmented with weather radar data), and other hailfall parameters has been available.

(iii) The New England Network

This was an investigation of New England hailstorms conducted in 1956, 1957 and 1958, during which time 317 hail reports were received (Donaldson, Chmela, and Shackford, 1960). A radar, located at Blue Hills, Massachusetts, was used by the project.

(iv) Alberta Hail Studies

A description of this project and data obtained by it are contained in Chapter III of this thesis.

(v) The Illinois State Water Survey

Using data from United States Weather Bureau stations and sub-stations, and from the Crop Hail Insurance Actuarial Association of Chicago, research has been done on Illinois hail-day statistics (Stout, Blackmer, and Wilk, 1960). A network of approximately one thousand volunteer observers was set up in central Illinois in 1958 covering an area of about thirty thousand square miles.

(vi) The South Dakota Networks

Using a network based on hail insurance claims in

South Dakota supplemented by data from the adjoining states of Minnesota, Iowa and Nebraska, Frisby (1962) investigated the relationship between hail damage and surface synoptic features. From the ten-year period of data from 1951 to 1960, Frisby was able to determine a number of the characteristics of hailfall distribution. The major part of this study was performed on data from the eastern half of South Dakota where observer-density was the highest, being in the order of one observer per square mile.

A more recent study of hailstorms in western South Dakota was made by Dennis, Schock and Koscielski (1970). In the summer of 1968, hailfall data were collected using approximately one hundred passive hail indicators. A number of radar sets and aircraft were also used by the project.

Hail Forecasting Methods

As was previously mentioned, there are definite geographical and topographical regions in which hail is more likely to occur than in others. In some areas cumulonimbus clouds and thunderstorms occur quite frequently, but are seldom accompanied by hail, while in others hail is frequently present. Thus, through a study of climatological data, it is possible to eliminate certain regions from consideration in the forecasting of possibly damaging hail, and to concentrate attention on the most affected areas. Also, from climatological data, the

seasonal distribution and the most likely time of day of hailfall can be obtained as an aid to forecasting (Paul, 1967).

With the development in the late 1930's of an extensive upper-air observational network in North America, an additional tool in the forecasting of convective activity in general, and hail activity in particular, became available. A number of workers in the field of severe weather forecasting have developed techniques to provide indications of atmospheric instability, based on measurements of various upper-air parameters.

(i) The Showalter Index

This index, developed by Showalter (1953) is determined as follows:

> "The 850-mb parcel (mountain areas use a higher level) is lifted dry adiabatically to saturation and then pseudo-adiabatically to 500 mb. The lifted 500-mb temperature is then subtracted algebraically from the observed 500-mb temperatures. A negative number indicates instability (rising air warmer than its surroundings) and a positive number indicates stability."

Critical values of the index for showers, thunderstorms, and severe thunderstorms are listed in Table I. In order to use this index to make a forecast of convective activity, it is necessary to first make a forecast of 850-mb temperature and dew point and the 500-mb temperature for the time and area under consideration. A value of the index applies to a limited area because of the horizontal variability of the 850-mb parameters.

TABLE I

CRITICAL VALUES OF A NUMBER OF CONVECTIVE FORECASTING INDICES

Showalter index	Greater than 3°C - no convective activity 1° to 3°C - showers probable, thunderstorms quite probable -3° to +1°C - thunderstorms probable -6° to -3°C - severe thunderstorms probable less than -6°C - tornadoes possible
George's K Factor	Less than 20 - no convective activity 20 to 25 - isolated thunderstorms 25 to 30 - widely scattered thunderstorms 30 to 35 - scattered thunder-storms 35 or more - numerous thunderstorms
Totals index	Vertical totals less than 26 - no convective activity Vertical totals greater than 26 and cross totals: less than 18 - no thunderstorms 18 to 19 - isolated thunderstorms 20 to 23 - scattered thunderstorms, few severe thunder-storms 24 to 29 - scattered to numerous severe thunderstorms 30 or more - numerous severe thunderstorms, scattered tornadoes
Pappas technique	Graphical forecast of hail or no-hail

TABLE I continued:

Slydex	Non-frontal situations - greater than 34.0, a minor hail-day - greater than 35.0, a major hail-day Frontal situations - greater than 33.0, a minor hail-day - greater than 34.0, a major hail-day

(ii) George's K Factor

This technique attempts to combine in an index "K" the thermodynamic features of the temperature lapse rate, the moisture at 850 mb, and the depth of the moist layer (George, 1960). K is defined by the following formula:

$$K = T_{850} - T_{500} + T_{D850} - (T - T_D)_{700}$$

where T_{850} is the temperature at 850 mb, T_{500} is the 500-mb temperature, T_{D850} is the dew point at 850 mb, and $(T - T_D)_{700}$ is the temperature-dew point spread at 700 mb. Critical values of K for various types of convective activity are listed in Table I. Like the Showalter Index, George's K factor requires a forecast of the input parameters for each area for which a forecast of the convective activity is to be made. A number of subjective modifications are applied to the forecast of convective activity produced by using K.

(a) Average confluence on the 850-mb and 700-mb

charts increases the degree of convective activity that is forecast.

(b) Average diffluence on the same charts decreases the degree of convective activity that is forecast.

(c) Anticyclonic shear greater than 20 knots in 250 miles, measured towards low pressure from the station in question, prevents thunderstorm activity.

(d) The severest storms occur within two degrees of latitude of the cold pool at 200 mb, the temperature of the cold pool normally being less than or equal to minus 60 degrees Celsius.

(iii) Totals Index

The Totals Index recognizes the importance of the following three factors in making the atmosphere more unstable, (Miller, 1967)

> "a. Holding the top of the air column constant or warming it slightly, and adding heat and moisture to the bottom.
>
> b. Cooling the top of the column and holding the lower-level temperature and dew-point values nearly the same.
>
> c. The simultaneous occurrence of cooling at the top and heating at the bottom of the air column (which seldom happens)."

The Totals Index is made up of two factors--the vertical totals and the cross totals given by the following formulae.

Vertical total = $T_{850} - T_{500}$

Cross totals = $T_{D850} - T_{500}$

Totals index = Vertical totals + Cross totals

where the symbols are the same as for George's K Factor. The critical values of these parameters are listed in Table I. As with the two previous indices, a forecast must be made of the input parameters for the area for which the convection forecast is to be made.

(iv) Pappas' Forecasting Technique

Taking into account the cloud depth, the cloud depth below the freezing level, and the height of the freezing level, Pappas developed a "yes-no" hail-forecasting technique (Pappas, 1962). These factors that were considered were approximated as follows.

(a) Cloud depth: convective condensation level minus equilibrium level

(b) Cloud depth below the freezing level: convective condensation level minus the freezing level

where the heights of the various levels are measured in millibars. The equilibrium level is defined to be the level at which a surface parcel, under adiabatic ascent, which has become warmer than the surrounding air and subject to buoyancy forces upwards, acquires a temperature equal to that of the environment. It is, then, the level at which a surface parcel rising as the result of convection ceases to have an upward buoyancy force ex-

erted upon it.

From an investigation of seventy severe convective storms, thirty-four with hail and thirty-six without, in the south-central United States in 1959 and 1960, Pappas prepared a graph of the ratio of (b) to (a) versus the height of the freezing level and the occurrence or non-occurrence of hail. It is difficult to apply Pappas' technique operationally because it requires the preparation of a complete forecast upper-air sounding in order to determine the input parameters. It should also be noted that the technique applies only to situations that are already convective, and indicates whether or not they will be hail-producing. The technique must also be modified for use in areas other than the one for which it was developed because of the different characteristics of hail-producing clouds from region to region.

(v) The Slydex

The Slydex (Sly, 1965, 1966, 1967) has been extensively used in the forecasting of Alberta hail because it was developed using hail data obtained in central and southern Alberta by the Alberta Hail Studies project. Sly recognized the following atmospheric conditions as being conducive to hail occurrence.

"(a) A steep lapse rate of the dry-bulb temperature to a considerable height.
(b) Moist air in the lower levels
(c) Potential instability
(d) Vertical motions due to one or more of the following:
  i) dynamic forces

ii) frontal lift
iii) orographic lift"

In an attempt to reflect these influences, Sly devised an index C_2 given by the following equation:

$$C_2 = 1.6\theta_w - T_{500} - 11$$

where θ_w is the wet bulb potential temperature at station level in degrees Celsius, determined by using the 2100 GMT dew-point temperature and the maximum temperature of the day, T_{500} is the 500-mb temperature (°C) at 0000GMT the following day (1700 MST on the same day) and 11 is a number chosen originally by Rackliff (1963) in order to give to a similar index, which he derived, the same critical values as a previous index. Critical values of the Slydex for minor and major hail-days are given in Table I. Sly defined his hail-days as follows.

no hail - fewer than ten reports of hail from the project area

minor hail day - ten to forty-nine reports, one of which was pea-size or larger

major hail day - fifty or more reports, one of which was pea-size or larger

Sly also investigated the usefulness of drawing convective index charts, consisting of isopleths of Slydex values (Sly, 1967). It was found that there was a greater concentration of hail near relative maxima of the index. Nearly all cumulonimbus activity in western Canada during the afternoon and evening was with-

in the boundaries of the 31.0 isoline. Widespread hail was generally associated with a Slydex value of 34.0 or greater. There is considerable difficulty in preparing forecast charts because all the input parameters must be forecast for a large number of stations, many of which do not have radiosonde ascents to give the 500-mb temperature. There is also the problem of forecasting the 2100 GMT dew-point, a very variable quantity in western Canada.

A number of attempts have been made to associate high wind speeds aloft and strong vertical wind shear with the occurrence of hail and convective activity.

(i) Dessens

After analysing thunderstorms in southwest France, Dessens (1960) concluded that strong upper-level winds were a determining factor in whether or not a thunderstorm produced hail. He examined thirty-eight days on which there was damaging hail, and thirty-eight days with thunderstorms but no significant damage. On only one day did the maximum wind velocity exceed twenty-five meters per second without the occurrence of damaging hail. A relationship was also suggested between the maximum horizontal wind and hail size.

(ii) Ratner

Shortly after the publication of Dessens' article (Dessens, 1960), Ratner (1961) wrote a criticism entitled "Do High-Speed Winds Aloft Influence the Occurrence of

Hail." Using rawindsonde data for the United States, Ratner examined 103 days in 1958 on which hail occurred, 103 days with thunderstorms and no hail, and 103 on which neither thunderstorms nor hail were reported. He concluded that neither the speed of winds aloft nor the wind shear between 500 and 250 mb were determining factors in the occurrence of hail. In a defence of his position, Dessens (1961) pointed out the differences between his hail categories and those of Ratner. Dessens considered only two categories: days without hail or with hail producing light or moderate damage, and days with heavy, widely destructive hailstorms. It would also seem that Ratner used very sparse hail data. The source of his data is not mentioned, but it seems likely that he used only U. S. Weather Bureau stations, or perhaps only the rawindsonde stations from which he obtained his wind data. Another apparent objection to Ratner's article is the manner in which he considered the values of wind shear and maximum wind speed. These were averaged over very large geographic areas, a technique which might tend to smooth out the important effects of a jet maximum on the maximum wind.

(iii) Schleusener

Using the 500-mb wind component, calculated every five degrees latitude along 110 degrees west longitude, Schleusener (1962) sought a correlation between the departure of this wind from the norm, and the occurrence of

hail in the lee of the Rocky Mountains. His hail data were obtained from the Colorado State University network for 1959 and 1960, and from the Alberta Hail Studies network for 1960. He found the following two factors to be significantly correlated with heavy hail.

"(a) Passage of a 'Relative velocity maximum' in Colorado in May . . .

(b) An increase in the positive anomaly south of the latitude of hail occurrence. (for both Colorado and Alberta . . .)"

Schleusener's association of high hail probability with the passage of a "relative velocity maximum" is similar to the results obtained by Dessens (1960). Dessens found that strong winds aloft were frequently associated with large hail.

The positive anomaly to which Schleusener refers is an increase in the 500-mb geostrophic wind above the normal value. An increase in the positive anomaly south of the latitude of hail occurrence could be a reflection of the effect of cold lows moving into the hail activity area (Longley and Thompson, 1965). Cold lows frequently have jet streams associated with their southern edges and would thus result in the increase in the positive anomaly.

(iv) Proppe

Proppe (1965) considered the relationship between hail in the Alberta Hail Studies area and wind shear obtained from the radiosonde ascents at Edmonton and Calgary. This study was performed using 1964 data only. Wind shears using all possible combinations of the manda-

tory reporting levels (850, 700, 500, 400, 300, 250, 200, and 150 mb.) were considered, and were related to a hail severity index. The following are some of the results that he obtained.

(a) Shears increasing with time, or at a local minimum, were associated with hail-free days.

(b) Shears decreasing with time, or at a local maximum, were associated with hail days.

(c) Smaller mean shears were associated with hail days.

(d) Strong advection of instability was associated with hail days.

(e) No correlation was found between the maximum wind strength and hail severity (c.f. Dessens).

Several attempts have been made to relate hailstorm activity to various combinations of atmospheric parameters.

(i) Longley and Thompson (1965) considered relationships between data obtained by the Alberta Hail Studies project from 1959 to 1963, and radiosonde data from stations in western Canada and the northwest United States. Correlations were found to exist between hail and the presence of unstable, warm, moist air, a cold vortex approaching from the west, and a fresh outbreak of cold air from the north. These phenomena were considered to be reflected by the heights of standard pressure levels and the upper air temperatures at Great Falls, Edmonton, Seattle, Prince

George, Fort Nelson, Annette Island, and Fort Smith. Some studies were also done using the 1961 and 1962 Calgary radiosonde data (available for the summer months from July 1961 until August 1968). These data from Calgary are particularly useful because they reflect the actual conditions in the Alberta hail belt better than the Edmonton or Great Falls radiosondes. One interesting result obtained from the Calgary data by the authors was that no hail fell when the 700-mb temperature was below -6°C, and that there were only four days with major hail when this temperature was below -2°C (for the years 1961 and 1962, consisting of a total of five months of data).

(ii) Using hail claim data from the northern Plains States and southern sections of the Prairie Provinces, Frisby (1965) related hail activity to the surface wet-bulb potential temperature, the 300-mb wind strength, and the presence of orographic or frontal lift. A diagram of the relationship between wet-bulb potential temperature and the 300-mb wind strength, and the occurrence of hail was presented. A method of preparing routine damaging hail forecasts was suggested. A number of actual forecasts and very convincing verifications thereof provided.

(iii) Thompson

Thompson (1970) performed a study that related the occurrence and characteristics of hailswaths to a

number of atmospheric parameters. A system of classifying hail activity was suggested as follows:

Swath hail-day - one or more hailswaths with the number of hail reports in swaths more than two-thirds of the total

Scattered swath hail-day - one or more hailswaths with less than two-thirds of the total number of reports in swaths

Scattered pattern - no hailswaths

Using data obtained by the Alberta Hail Studies project Thompson found that more directional wind shear for the 700 to 200-mb layer was associated with scattered swath hail-days than with swath hail periods. Also, 700-mb mean wind speeds were found to be greater for swath hail-days than for others. One other result obtained by Thompson was that on 94 per cent of swath hail-days the 700-mb temperature was greater than or equal to -2°C.

The two factors that are essential for a useful study of hail forecasting methods are a sufficiently dense hail reporting network, and the presence of a number of radiosonde stations in the study area. These factors are both present in the Alberta Hail Studies project area, described in Chapter III.

Using the Alberta Hail Studies data, this thesis attempts to relate wind shear, along with some other upper-air parameters, to the occurrence of hail. Origin-

ally it was intended that this study would be limited to the consideration of wind shear alone, but, after reviewing the results of other investigators in this field, it was decided that other factors should be taken into consideration. The results of a number of studies relating vertical wind shear with the occurrence of hail are presented in the next chapter.

CHAPTER II

THEORY OF THE CONNECTION BETWEEN WIND SHEAR AND HAILSTORMS

The effect of vertical wind shear on convective activity has been under study for some time. Dessens (1960) drew the analogy between a convective cell and a chimney that draws well in a strong wind. Lacking shear, energy is fed in at the cell's base but none is removed at the top, analogous to a chimney that fails to draw. When shear is present, however, the air column is inclined to the vertical, part of the rising air in the cloud is mixed with environmental air, and there is a coupling between the updraft and the strong horizontal current that prolongs the life of the chimney. Dessens also suggested that strong shear can break up weak cells by providing too much mixing. In this situation, parcels of rising air would be mixed so thoroughly with the environment that there would not be a sufficient temperature difference between the parcels and the environment for strong convection to take place.

Das (1962) developed a mathematical model of a cloud incorporating wind shear in which he simulated the growth of hailstones. He found that hailstone embryos of the same initial size grew to be forty per

cent larger in radius when they fell out in the no-shear case than in the shear case. However, the no-shear case required some means of preventing the hailstones from being lifted into a cloud area where all the products of condensation were frozen. This requires a deceleration of the updraft velocity. In the case of a cloud with shear, this deceleration is provided by the hailstone's being blown horizontally into a region of weaker updraft. Das concluded that strong wind shear aloft favored the occurrence of hailstones in a thunderstorm, but suppressed the maximum size attainable for a given temperature-moisture regime.

A model of a steady-state hail-generating cell without shear was developed by Hitschfeld and Douglas (1963). They found that by the time hailstones had fallen to near ground-level they were very slushy because they had been in regions of the cloud with high moisture contents for a long period of time. They felt that if the hailstones had moved to regions of lower water content they would have remained drier. This movement could have been accomplished by the presence of strong vertical wind shear. Also, strong shear would have prevented many of the particles being lifted too high for substantial development.

Newton (1960, 1967, 1968) discussed the influence of vertical wind shear on convective activity and the occurrence of hail. The wind field around a convec-

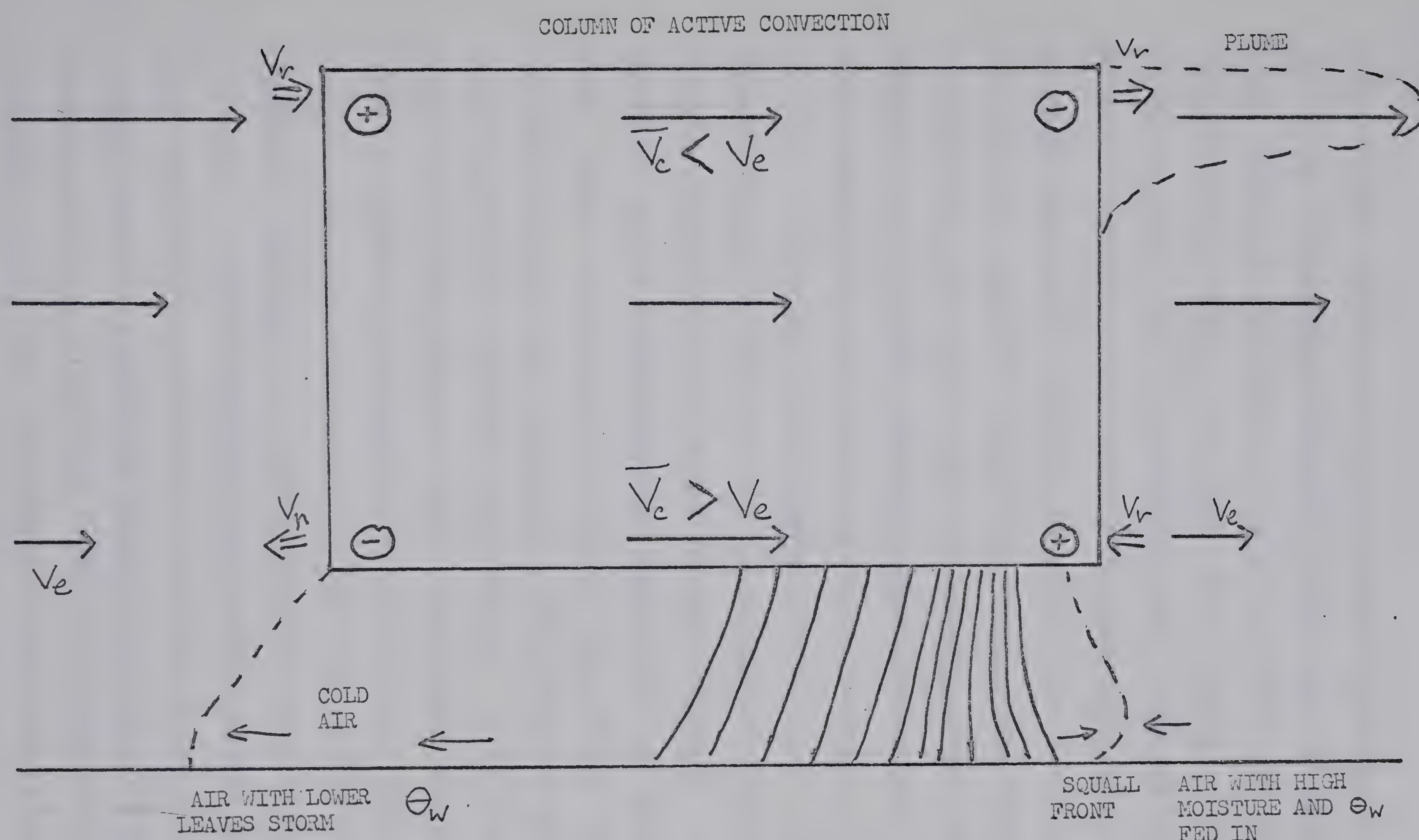

FIGURE 1 - PRINCIPAL COMPONENTS OF A LARGE SHEARED THUNDERSTORM (Newton, 1968)

tive cell was considered to be as shown in Figure 1, where V_e is the environmental wind, $\overline{V}_c$ is the mean in-cloud wind, and V_r is the relative wind, the difference between $\overline{V}_c$ at a given level in the storm column and V_e at that level ($V_r = V_e - \overline{V}_c$). $\overline{V}_c$ differs from V_e because of the vigorous updrafts in the column of convection which exchange momentum. The plus and minus signs in Figure 1 indicate the signs of the non-hydrodynamic pressures induced by V_r near the upwind and downwind sides (with respect to V_r) of the column of active convection. This induced pressure P is given by the formula:

$$P = \rho V_r^2/2.0 \quad \text{(Newton, 1967)}$$

where ρ is the density of air, and where the convective cell is considered to be a cylindrical obstacle. P is positive on the upwind side and negative on the downwind side. This non-hydrostatic pressure term, which varies in magnitude and sign depending on the direction of V_r, acts to produce a vertical acceleration. It is a positive term on the downshear side of the cloud, and thus tends to promote new convection in this area. Also, because new convective cells have the most vigorous updrafts, this area is a prime hail-producing part of the cloud. Newton concludes that strong vertical wind shear and pronounced veering of the wind direction with height (warm air advection) favours the growth of new convection on the right hand flank of a rainstorm (the downshear side), that the aforementioned induced pressure

gradient force augments the upward accelerations provided by buoyancy, that the downshear flank is favorable for large-hail growth because it is an area where the updrafts are shielded by the storm itself from entrainment of dry air at upper levels, and that all of these results apply, in general, only to vigorous rainstorms of large horizontal extent.

The consensus of opinion on the theoretical effect of vertical wind shear on the occurrence of hail seems to be that the presence of strong shear, associated with strong convection, enhances the probability of hailfall. Vertical wind shear is not, however, a necessary condition for hailfall, and does in fact suppress larger sized hail, and in the case of weak convective cells may even suppress development by shearing off the clouds' tops.

CHAPTER III

THE DATA USED AND METHODS OF ANALYSIS

The hail data used in this study were obtained by the Alberta Hail Studies project in central and southern Alberta during the months of June, July, and August, from 1956 to 1967 inclusive. The project has a mean observer-density of one per square mile, although this value varies considerably over the project area because of variations in population density. The project area is shown in Figure 2.

Initially, it was necessary to devise a method of classifying days as no-hail, minor hail, or major hail days. A number of classification systems have been used in Alberta. Quon and Thompson (1963), for example, used the following classification:

less that 10 reports - no-hail day
10 to 49 reports - minor hail day
50 or more reports - major hail day

based on Longley and Thompson's (1961) original classification for hail activity in Alberta. These Figures have been revised upwards in recent years (Lawford and Currie, 1968), as a result of the ever-increasing number of observers. This classification gives the same weight to

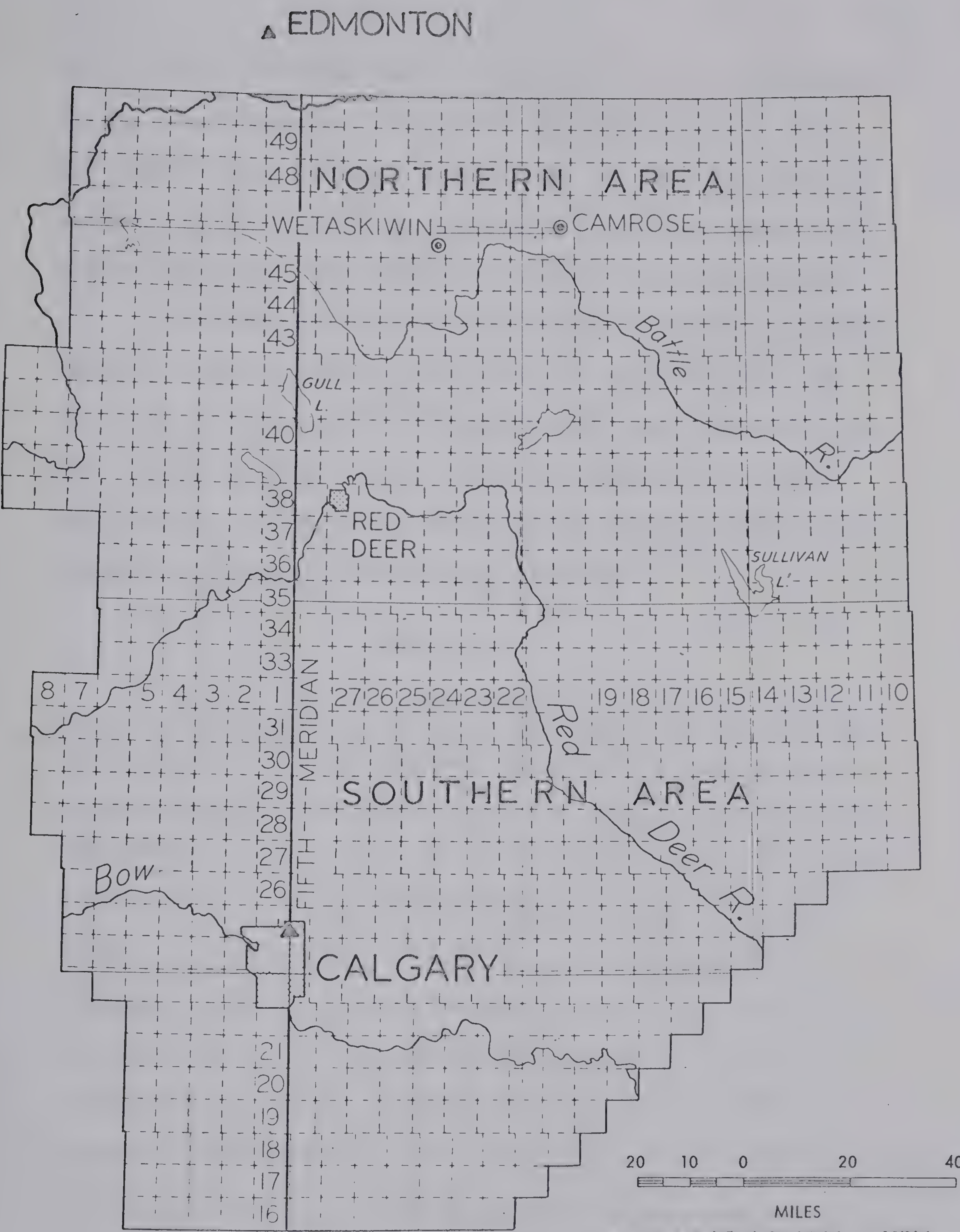

FIGURE 2 - THE ALBERTA HAIL STUDIES PROJECT AREA

each report, whether the hail diameter be two millimeters or two centimeters. Sly (1965) suggested that a hail day should have at least one report of pea-size hail or larger, in an attempt to eliminate very cool days on which soft hail fell causing little or no crop damage.

It seemed that a useful index would be one which took into account both the number of hail reports and the size distribution on a particular day. Because the hail sizes in Alberta Hail Studies reports are coded numerically, as shown in Table II, a simple method of classification was immediately obvious.

TABLE II

HAIL SIZE CODE

Hail Size	Assumed diameter (mm)	Size Code
No-hail	-	0
Shot	Less than 3	1
Pea	3 to 12	2
Grape	13 to 20	3
Walnut	21 to 30	4
Golfball	31 to 50	5
Larger than Golfball	More than 50	6

The size used in developing the index is that of the largest hailstones reported by each observer. The size codes of all reports for the day being considered

were summed, and the following classification used.

less than 15	-	no-hail day
15 to 99	-	minor hail day
100 or more	-	major hail day

The figure of 15 as a lower boundary for a minor hail day was chosen to allow for errors in the date of hail-fall reported by the observers. The value of 100 as a lower boundary for a major hail day was chosen on a subjective basis, as a value that would reflect wide-spread hail and/or fairly large sizes. It is interesting to note than an index value of 100 could be made up of 100 shot size, 50 pea size, 25 walnut, or 20 golfball size reports.

Other indices involving the sum of the squares of the size codes, and the sum of their cubes, were considered, because they would be proportional to the cross-sectional area and the volumes of the hailstones respectively. Both of these indices over-emphasized large-sized hail. An erroneous report of walnut-size hail (code 4) would give a cube index value of 64 and a square index value of 16, whereas a considerable number of smaller sized hail reports would be necessary to attain these index values. Therefore, these two indices were not used in the analysis, but are shown in the examples in Table III to illustrate their orders of magnitude and their variations.

TABLE III

HAIL-DAY INDICES

Number of Hail Reports	Sum of Size Codes	Sum of Squares of Size Codes	Sum of Cubes of Size Codes
10	24	60	156
196	694	2,664	10,978
1	4	16	64
170	473	1,499	5,309
218	424	1,010	2,104
21	45	105	261
16	46	138	430

Table III illustrates how the indices involving hail sizes give a better measure of the severity of hail on a particular day. Comparing line two with line five, one can see that, while the number of hail reports was approximately the same, the sum of the size codes for the former is considerably larger than for the latter. The problem with the sum of cubes index can be seen by comparing lines one and three. While line one has ten times as many reports as line three, the cube index is only a factor of three larger. This illustrates how one erroneous report of large-size hail can result in a considerable error in the square and cube indices. It was decided to work with just the sum of size codes index, even though it is not a measure of the hailstone mass or

energy, because it does take into account the distribution of hail sizes and is not affected very much by erroneous reports.

A number of restrictions were placed on the hail reports that were considered in this study. Only unsolicited reports[1] for which the time of hailfall was between 1200 and 2200 hours MST were considered. Unsolicited reports were used because they are the most representative reports for all varieties of hail days. There is a problem on days on which surveys are made because these tend to reduce the number of unsolicited hail reports received. However, because surveys were normally performed only on active hail days, the reduction in the number of unsolicited reports received was not considered to affect a day's classification significantly. The restriction of the time of hail occurrence to between 1200 and 2200 MST was thought necessary if a correlation with the 0000 GMT (1700 MST) radiosonde was to be examined.

Upper air data were obtained from the Edmonton and Calgary radiosonde ascents. Edmonton data were available for the entire period of the hail data for both 0000 and 1200 hours GMT, while Calgary data were available only after 1961. Some initial analysis was done using data

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[1]An unsolicited report in the Alberta Hail Studies project area is defined to be one which was mailed or phoned in by an observer, rather than one which was obtained by a car or telephone survey.

from both sites, the project area being divided by an east-west line halfway between Calgary and Edmonton, as shown in Figure 2. Smaller values of the hail-day criteria were used in considering these smaller areas.

It was decided, however, to concentrate more on the Calgary ascent because it has been proven to be much more representative of the airmass over the project area than Edmonton's, which is normally in a more stable airmass (Longley and Thompson, 1965). Also, only the 0000 GMT (1700 MST) ascent was considered, because this time is very close to the time of maximum convective activity in Alberta (Paul, 1967).

Several upper air parameters were considered with respect to their relationship to the occurrence of hail.

(i) Vertical Wind Shear

Vertical wind shear is defined to be the vector difference between the horizontal wind velocity at two levels (Figure 3). In this study the shear was calculated for the layer from 850 to 300 mb, because the former is close to the base of convective clouds in Alberta, and the latter close to the average height of their tops, and to the average height of the level of maximum wind speed. In addition, these two levels are ones for which routine analyses are prepared by the Central Analysis Office of the Canadian Meteorological Service. This will facilitate shear calculations on an operational basis should any of the results of this study prove to be useful in practical

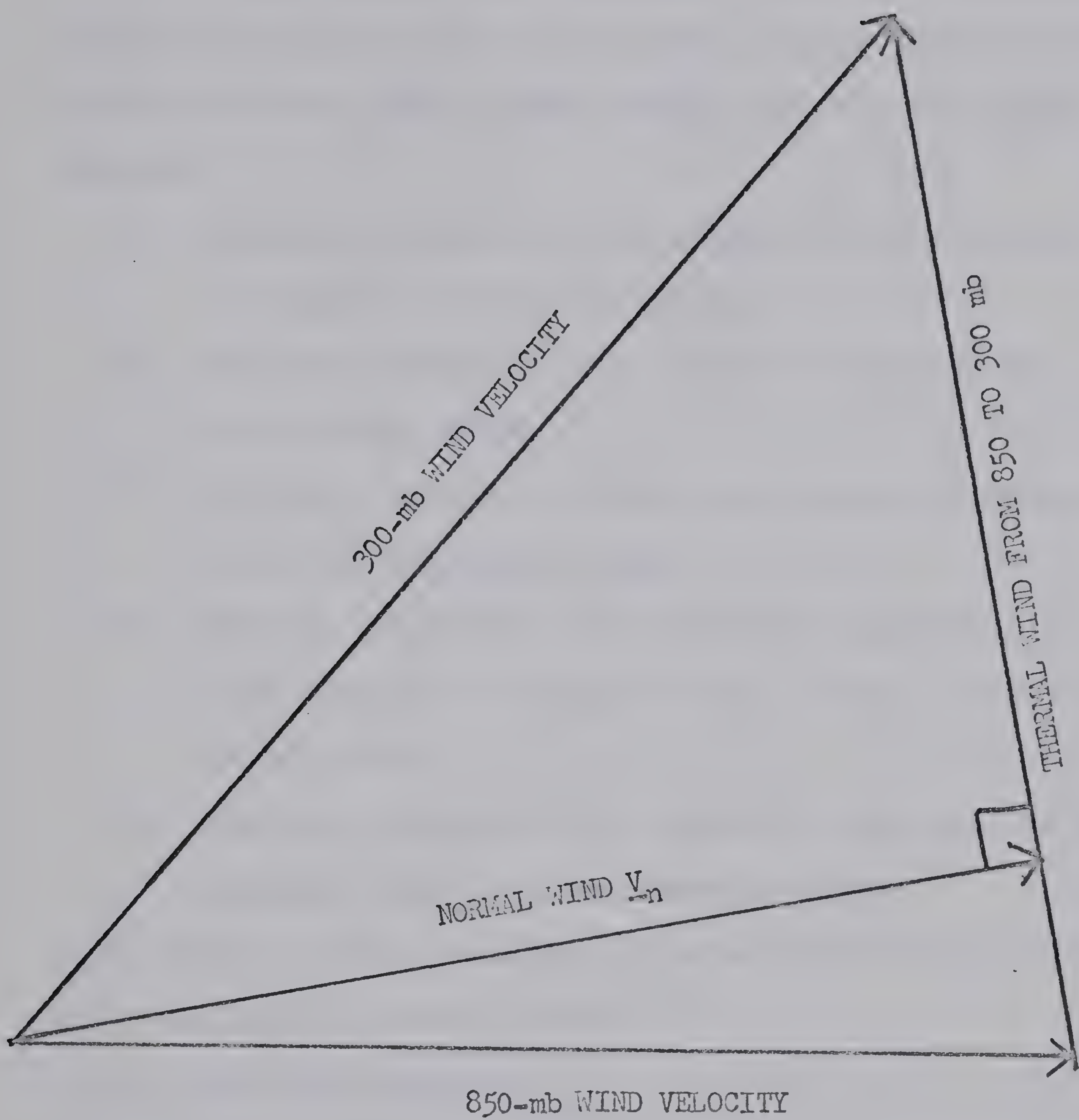


FIGURE 3 - THE THERMAL WIND

hail forecasting.

(ii) Upper Air Temperatures

Temperatures were available for all the mandatory reporting levels. The surface, 850, 700, 500, and 300-mb level data were used in this study, for the following reasons:

1. Surface - because it provides an indication of the degree of surface heating.
2. 850 mb - because it is close to the base of convective clouds
3. 700 mb - because it provides a means of estimating the freezing level
4. 500 mb - because it is close to the mid-point with respect to height of the average convective cloud
5. 300 mb - because it is close to the level of the average top of a cumulonimbus cloud

Also, analytic and prognostic charts are readily available for most of these levels.

(iii) Relative Humidity

Because the presence of low-level moisture is an important factor in the development of convective clouds (Frisby, 1965), the relative humidities and the associated temperatures, at the surface and at the 850-mb level, were considered.

Methods of Analysis of the Relationships between the Atmospheric Parameters and the Occurrence of Hail

The first step in determining the relationship between some atmospheric parameter and the probability of hail was to determine subjectively a suitable class interval. The major criterion used in choosing the class interval was that it contained a sufficient number of days to permit some meaningful probability to be calculated. Once the class interval had been decided upon, the probability of hail was determined for each interval by discovering the number of no-hail, minor hail, major hail days that had values of the atmospheric parameter under consideration that fell within the particular class interval.

Then, trend lines for the relationship between the atmospheric parameter and the probability of hail were determined using a least square regression technique. Each point that was fitted to a trend line was weighted by the number of days having parameter values within that particular class interval. The total number of days that were available to determine trend lines varied considerably, depending on the parameter being considered. More high-level data were missing than low-level data. The total number of days being considered varied from about 550 when surface data were used to about 400 when 300-mb data were used. For each trend line, a correlation coefficient r was calculated as a measure of the

association between the two variables under consideration.

When wind directions were being considered, the southerly component of the wind direction was the parameter considered. This was done because it has been recognized that the advection of warm air at some levels and the advection of cold air at others is an important factor in promoting convective activity. In Alberta, warm air is normally advected from a southerly direction and cold air, from a northerly one. The parameter plotted on the graphs in these cases was the cosine of the angle between the wind direction and south. For example, for a south wind the parameter value is 1, for a west wind, 0, and for a north wind, -1.

In all the graphs in this thesis, the following codes are used:

Solid line - Probability of major or minor hail

Dashed line - Probability of major hail

Dot - Major or minor hail points

Cross - Major hail points

P_1 - Probability of major or minor hail

P_2 - Probability of major hail

r - Correlation coefficient

CHAPTER IV

RELATIONSHIPS BETWEEN CALGARY AND EDMONTON RADIOSONDE DATA AND THE OCCURRENCE OF HAIL

An initial analysis was performed on both Calgary and Edmonton data for the years mentioned in Chapter III. The project area was split into two parts by an east-west line half-way between Edmonton and Calgary, as shown in Figure 2. Relationships were sought between hailfall in the northern area and the Edmonton radiosonde, and hailfall in the southern area and the Calgary radiosonde. Reduced values of the hail-day criteria were used for these smaller areas.

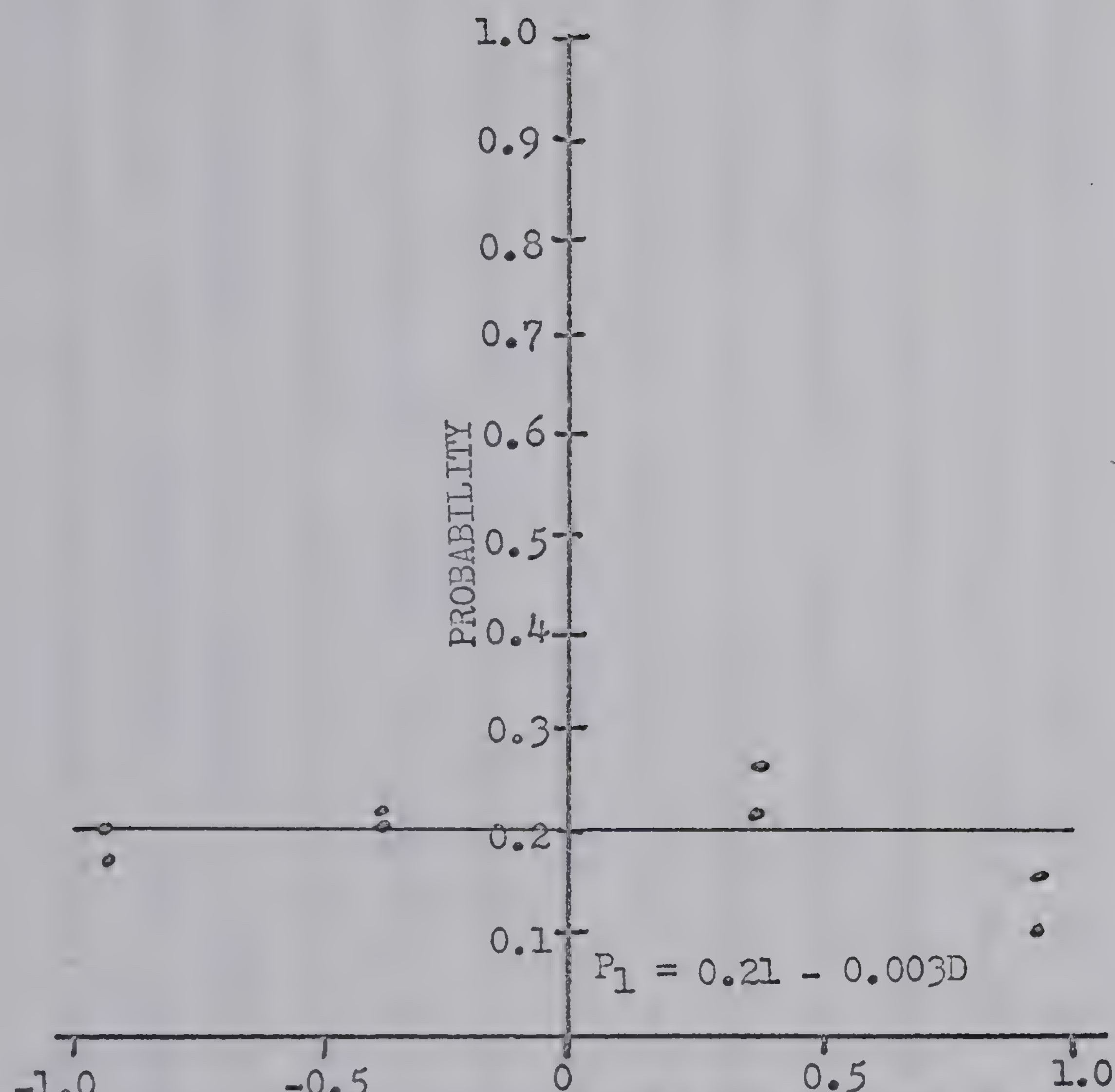
Sum-of-size codes:

less than 10 - no hail day

10 to 49 - minor hail day

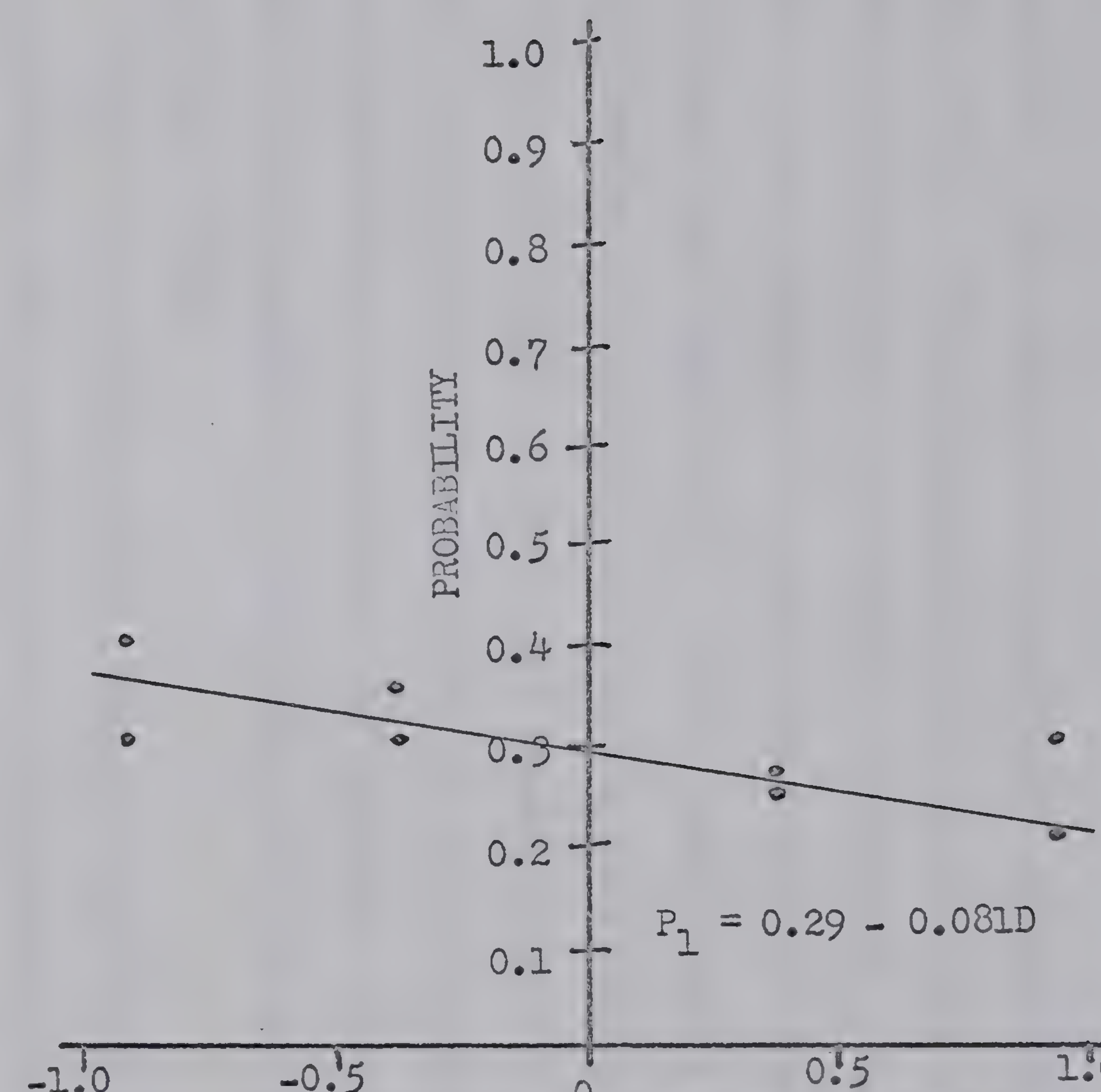
50 or more - major hail day

Figures 4a and 4b illustrate the relationships that were found between the 850-mb wind direction and the probability of a hail day. The quantity D referred to in the figures is the cosine of the differences between the 850-mb wind direction and south. For the southern region, P_1 varied from 0.20 for a south wind at Calgary to 0.40 for a north one, while in the north-



D, THE COSINE OF THE DIFFERENCE BETWEEN THE WIND DIRECTION AND SOUTH

FIGURE 4a - THE EFFECT OF D AT 850 mb AT EDMONTON ON THE PROBABILITY OF HAIL

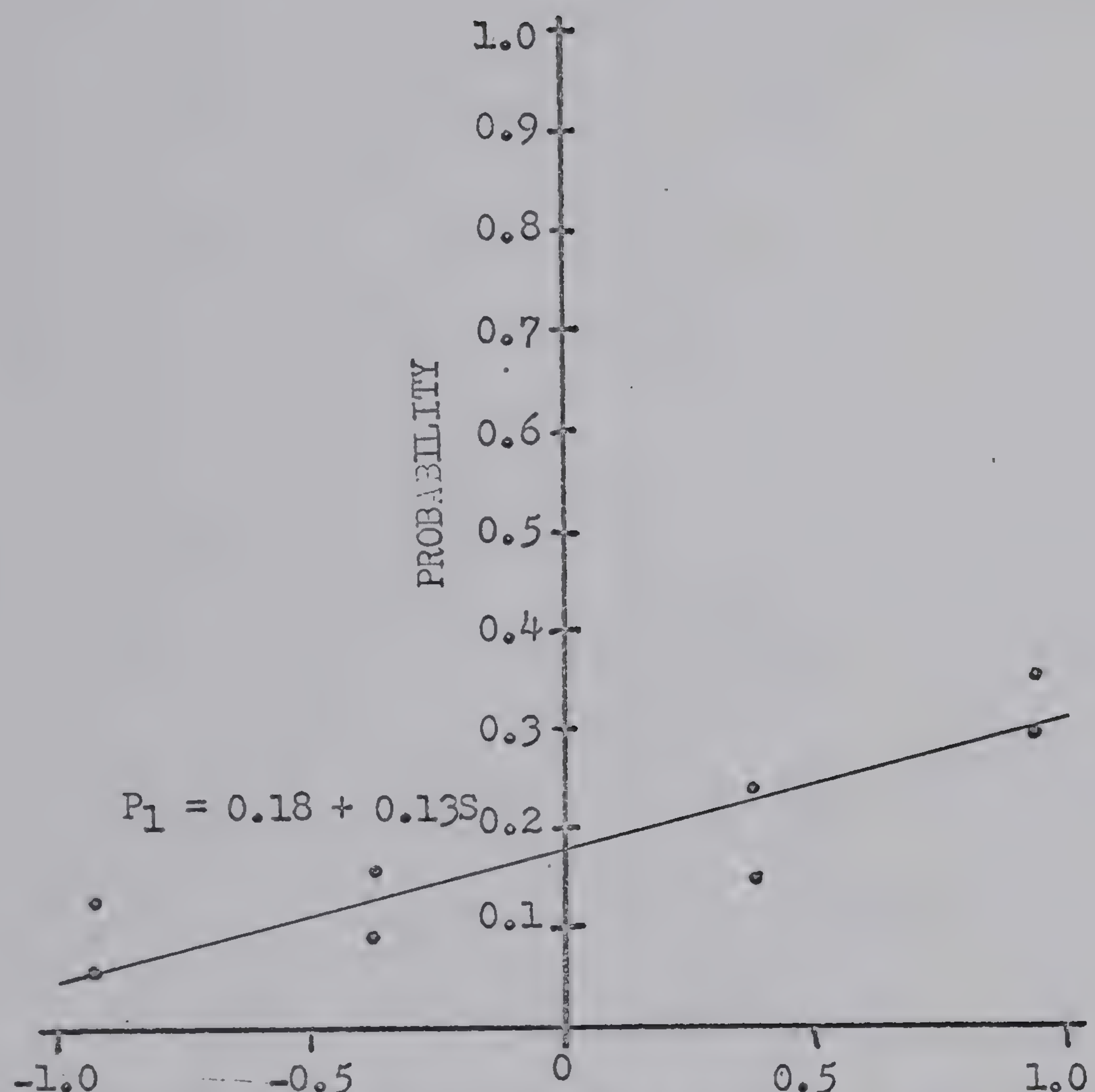


D; THE COSINE OF THE DIFFERENCE BETWEEN THE WIND DIRECTION AND SOUTH

FIGURE 4b - THE EFFECT OF D AT 850 mb AT CALGARY ON THE PROBABILITY OF HAIL

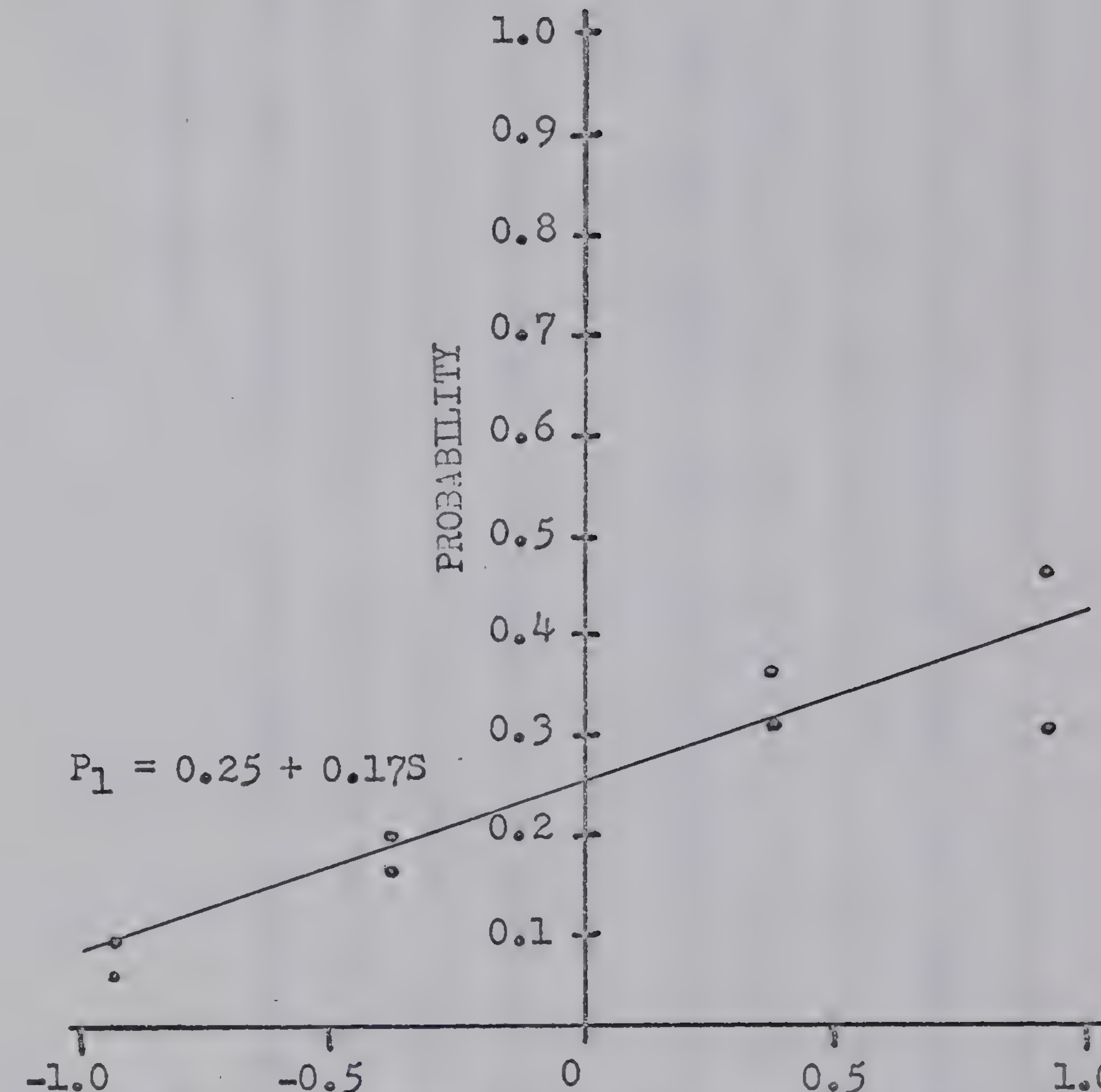
ern region P_1 was about 0.20 regardless of Edmonton's wind direction. The maximum of hail probability for northerly 850-mb winds at Calgary is probably a reflection of the effect of a cold front moving into the project area from the north. A cold front moving into central Alberta is normally associated with northerly 850-mb winds at Calgary and should increase convective activity by providing frontal lift. A similar result to this was obtained by Longley and Thompson (1965). The reasons for the absence of this effect in the northern region is not clear.

The relationships found between the 850-mb to 300-mb thermal wind direction and hail probability are shown in Figures 5a and 5b. Once again, the trend line for Calgary data had a steeper slope than for Edmonton. The quantity S used in the figures is the cosine of the difference between the thermal wind direction and south. For the northern region, P_1 varied from about 0.05 for northerly thermal winds to 0.30 for southerly ones, while in the southern region it varied from 0.08 for northerly ones to 0.42 for southerly ones. A number of other parameters were investigated for their relationship to the probability of hail. In general, it was found that for predicting hail in the southern area Calgary's radiosonde data were superior to Edmonton's in predicting hail in the northern area. This result was also mentioned by Longley and Thompson (1965) who pointed



S, THE COSINE OF THE DIFFERENCE BETWEEN THE DIRECTION OF THE 850 TO 300-mb THERMAL WIND AND SOUTH

FIGURE 5a - THE RELATIONSHIP BETWEEN THE DIRECTION OF THE THERMAL WIND AT EDMONTON AND HAIL PROBABILITY



S, THE COSINE OF THE DIFFERENCE BETWEEN THE DIRECTION OF THE 850 TO 300-mb THERMAL WIND AND SOUTH

FIGURE 5b - THE RELATIONSHIP BETWEEN THE DIRECTION OF THE THERMAL WIND AT CALGARY AND HAIL PROBABILITY

out that the Calgary radiosonde is more representative of the airmass over the Alberta hail area than Edmonton's, which is frequently representative of a more stable airmass. In fact, prior to the initiation of Calgary radiosondes, the Great Falls ascent was considered superior to Edmonton's for the forecasting of Alberta hail. Because of the superiority of Calgary radiosonde data in predicting hail in Alberta, the main analysis in the following chapter uses only Calgary data and attempts to relate this to hailfall in the entire Alberta Hail Studies project area.

CHAPTER V

RELATIONSHIPS BETWEEN CALGARY UPPER-AIR PARAMETERS AND HAIL PROBABILITY IN THE ALBERTA HAIL STUDIES PROJECT AREA

In this chapter the relationships between various upper-air parameters at Calgary and the probability of hail in the entire project areas are considered. This investigation can be divided into three classes on the basis of the type of upper-air data being considered.

(i) Winds

(ii) Temperatures

(iii) Combinations of winds, temperatures and relative humidity

(i) Winds

The relationships between the probability of a hail day and several upper-level wind parameters were investigated. The results of this investigation are shown as trend lines in Table IV, with correlation coefficients being given to provide a measure of the scatter of the data points about the lines.

(a) The 850-mb Wind Direction

The probability of any hail-day occurrence (major or minor) was graphed against D, the cosine of the departure of the 850-mb wind direction from south (Figure 6).

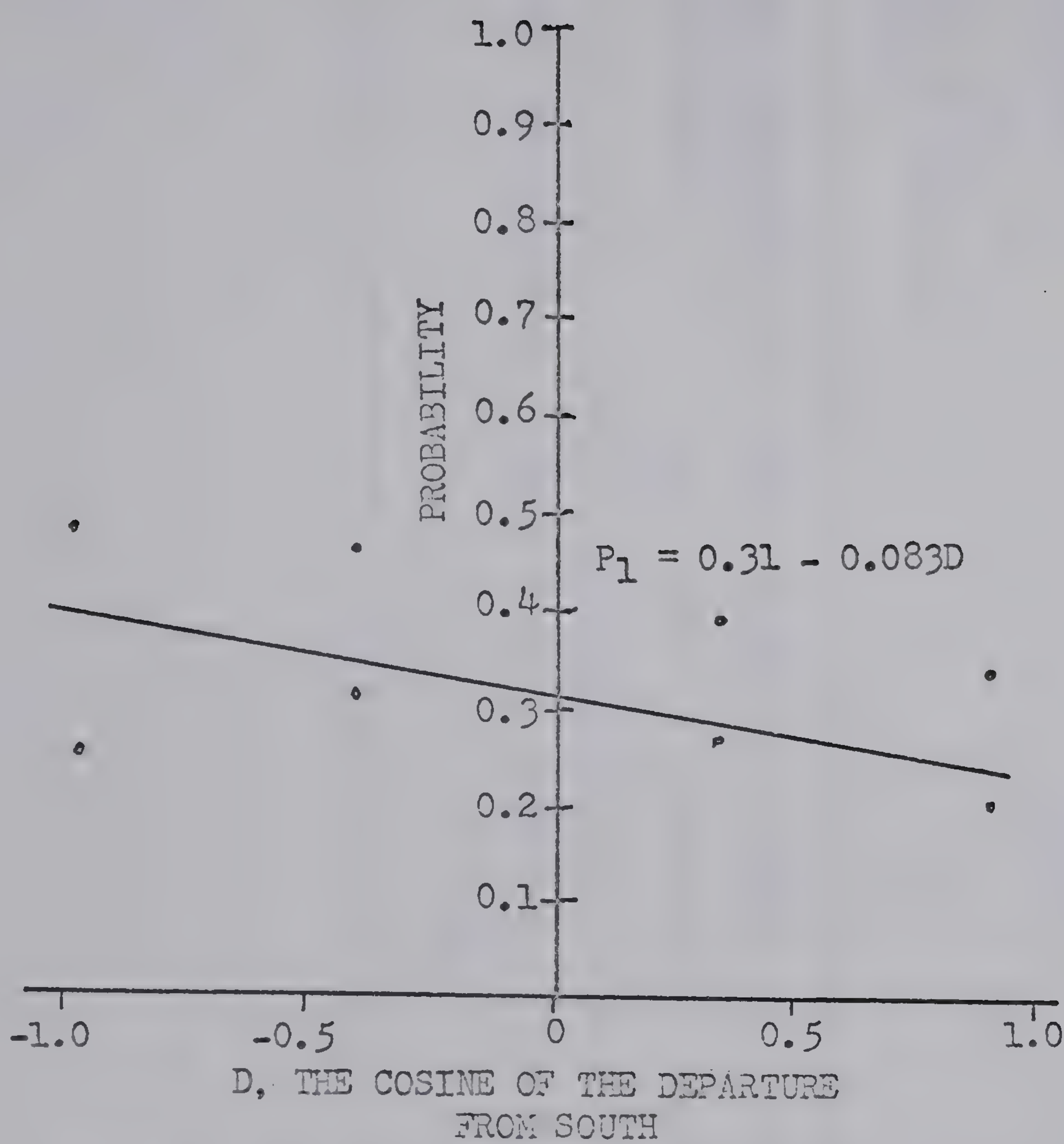


FIGURE 6 - THE RELATIONSHIP BETWEEN THE CALGARY 850-mb WIND DRECTION AND HAIL-DAY PROBABILITY P_1

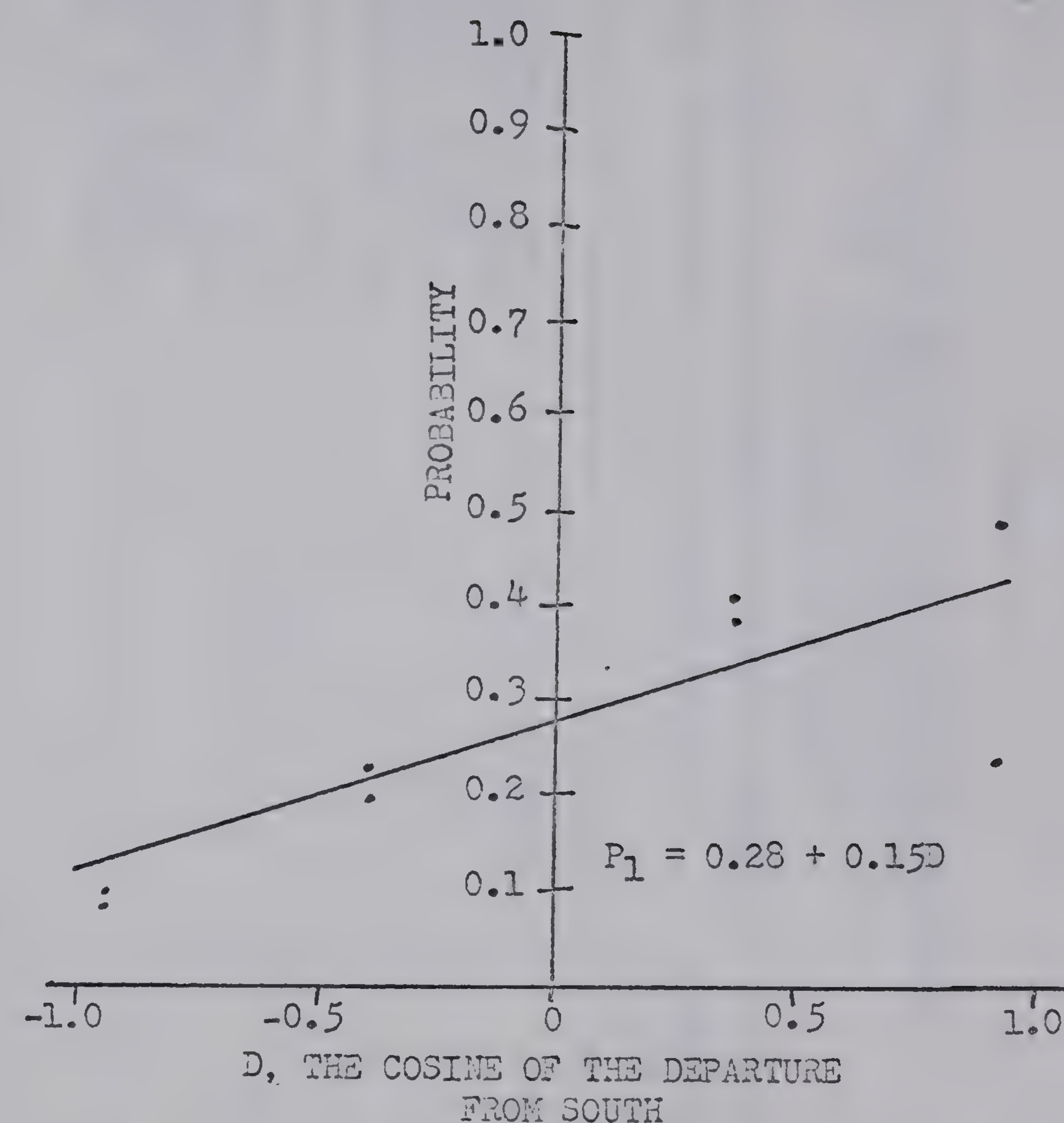


FIGURE 7a - THE RELATIONSHIP BETWEEN THE 850 TO 300-mb THERMAL WIND DRECTION AND THE PROBABILITY P_1 OF HAIL

TABLE IV

TREND LINES FOR THE RELATIONSHIPS BETWEEN WINDS ALOFT AND THE PROBABILITY P_1 OF ANY HAIL-DAY AND P_2 OF A MAJOR HAIL-DAY

Wind Parameter	Trend Line	Correlation Coefficient
Cosine of the departure from south of the 850-mb wind direction = D	$P_1 = 0.31 - 0.083D$	- 0.56
Cosine of the departure from south of the 850 to 300-mb thermal wind = D	$P_1 = 0.28 + 0.15D$	0.75
Magnitude V_t in m/sec of the 850 to 300-mb thermal wind	$P_1 = 0.28 + 0.00095V_t$	0.19
Warm advection A (for definition see text)	$P_1 = 0.26 + 0.00035A$	0.20
	$P_2 = 0.08 + 0.00046A$	0.30
Cold advection A	$P_1 = 0.41 - 0.00022A$	- 0.12
	$P_2 = 0.20 - 0.000002A$	- 0.01

It was found that the probability of hail decreased with increasing D. A maximum hail probability of 0.40 was noted for north winds, and a minimum of 0.23 for south ones. This is a reflection of the effect of cold fronts moving into the project area from the north. These are accompanied by northerly 850-mb winds and tend to increase convective activity by providing frontal lift. This is similar to the result obtained by Longley and Thompson (1965). They, however, considered the northwesterly component of the 850-mb geostrophic wind determined by subtracting the 850-mb level heights at Edmonton and Great Falls from those at Spokane and Prince George. Their method of analysing the effect of the direction of the 850-mb flow on hail probability may have been better than that used in this study. However, the longer period of record available for Calgary in this study than in theirs makes worthwhile a consideration of the relationship between the 850-mb wind direction at Calgary and the probability of a hail-day.

(b) The 850 to 300-mb Thermal Wind

Figure 7a illustrates the relationship found between the probability of hail and the cosine of the departure of 850 to 300-mb thermal wind from south. The probability of hail was found to be 0.13 when the thermal wind was from the north and 0.43 when it was from the south. A southerly thermal wind direction is associated with a greater southerly component at the higher level

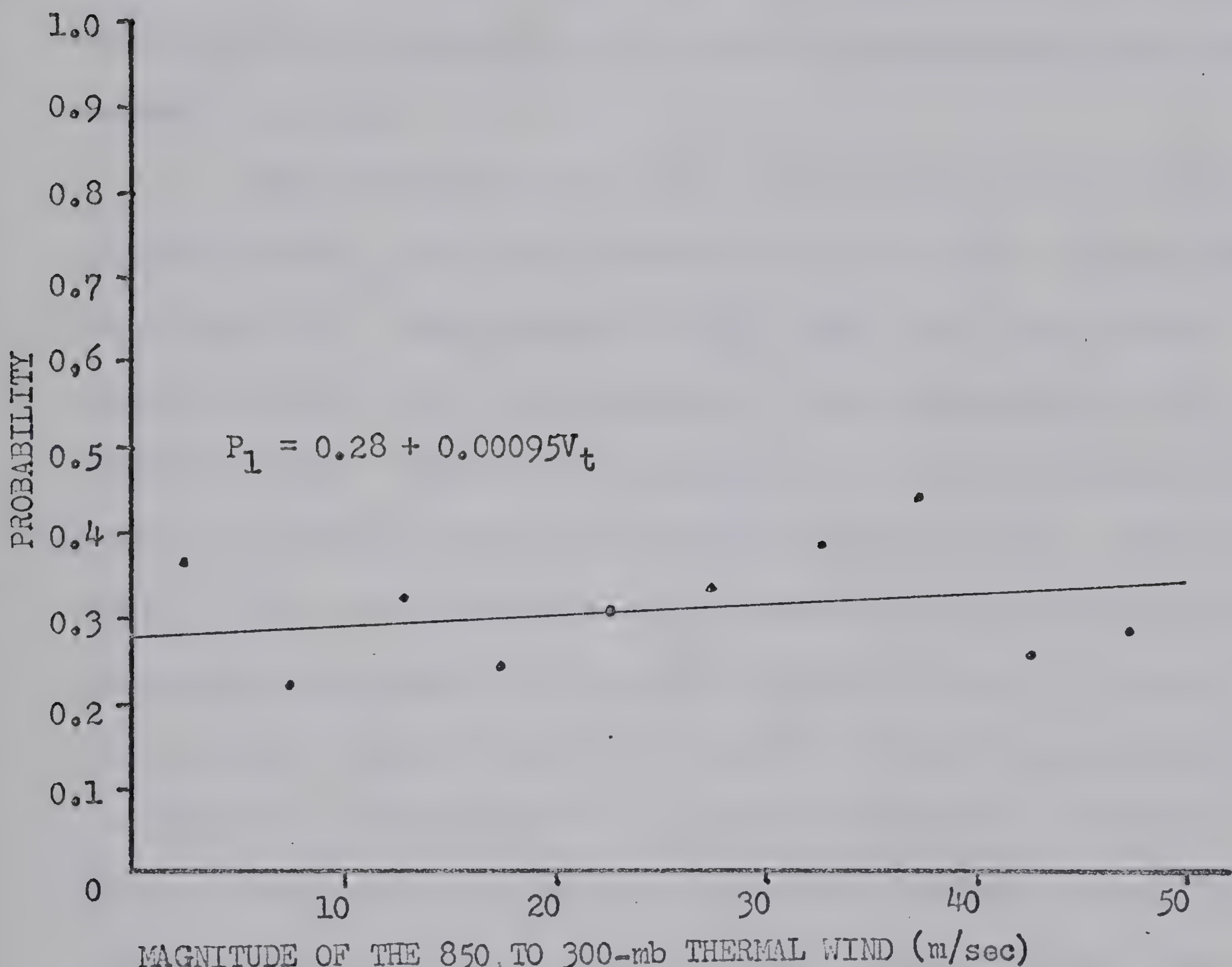


FIGURE 7b - THE RELATIONSHIP BETWEEN THE 850 TO 300-mb THERMAL WIND SPEED AND THE PROBABILITY OF HAIL

(300 mb) than at the lower level (850 mb). This is a situation that normally accompanies the passage of a cold front through the project area. When a cold front moves through, the wind direction in the lower levels normally shifts towards the north while the wind at higher levels remains more southerly because it is still representative of the warmer air mass.

The effect of the magnitude of the 850 to 300-mb thermal wind V_t on the probability of hail is illustrated in Figure 7b. The probability of hail was found to be approximately 0.30, regardless of the magnitude of the thermal wind. However, an examination of the points in Figure 7b does reveal two interesting features. The probability of a hail-day seems to increase significantly with increasing thermal wind speeds between 20 and 40 m/sec. Also, there appears to be a dropoff in hail probability for thermal wind speeds in excess of 40 m/sec. Both of these trends were suggested by Dessens (1960) as was outlined in Chapter II of this thesis. Proppe (1965) also found that strong thermal winds were associated with no-hail days.

(c) Thermal Advection

Figures 8 and 9 are graphs of the magnitude of the thermal advection versus the probability of hail. The area A referred to in the diagrams and trend lines is the product of the thermal wind and the normal wind as defined

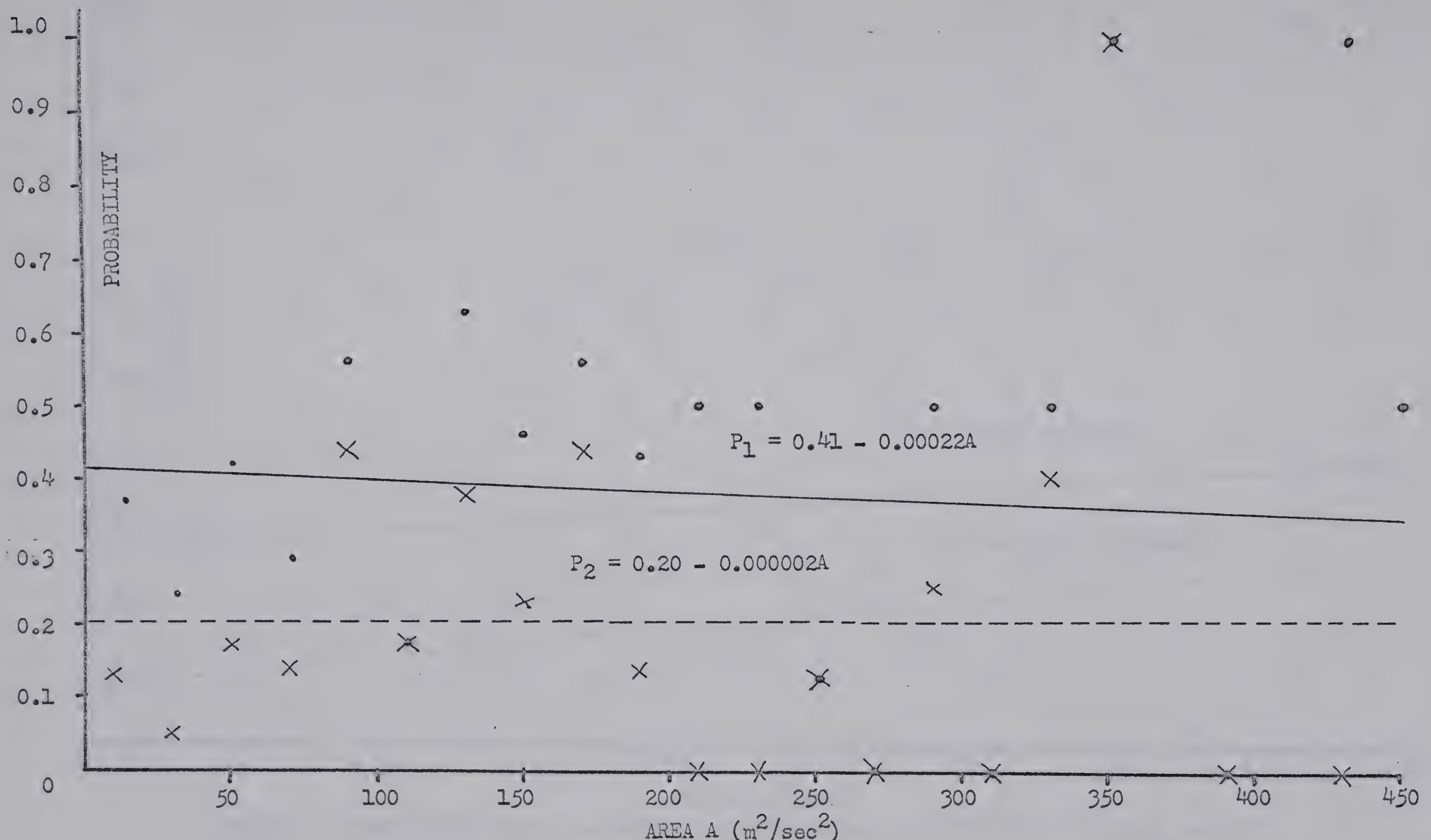


FIGURE 8 - THE RELATIONSHIP BETWEEN THE MAGNITUDE A OF THE COLD AIR ADVECTION AT CALGARY AND P_1 AND P_2

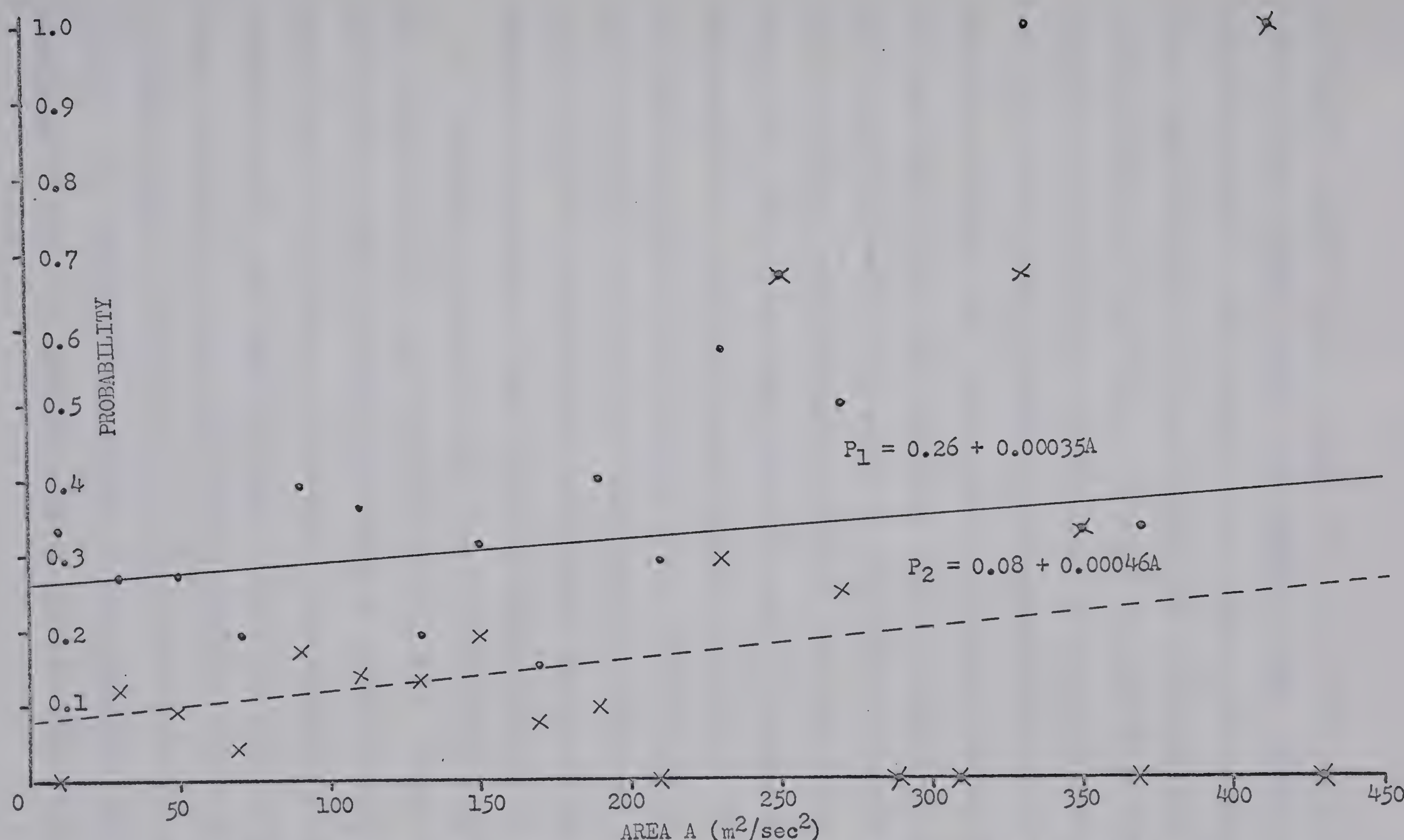


FIGURE 9 - THE EFFECT OF THE MAGNITUDE A OF THE WARM AIR ADVECTION AT CALGARY ON THE PROBABILITY OF HAIL

by Figure 2, and is equal to twice the area of the triangle formed by the 850-mb, 300-mb, and thermal winds. This area is proportional to the strength of the thermal advection. It was found that hail was more likely in cold advection situations than in warm ones. This is as would be expected because cold advection situations usually accompany cold-frontal activity which increases convective activity by providing frontal lift. There was little effect noted of the magnitude of the cold advection on the probability of hail, with the probability major or minor hail-day actually decreasing with increasingly strong cold advection (Figure 8). The reason that there is not an increase in hail-probability with increasing cold air advection, as one might initially expect, may be that in strong advection situations the cold front had passed the station (Calgary) some time before the radiosonde ascent and had ceased to provide any frontal lift to assist convection.

Hail-day probability was found to increase slightly with increasing warm air advection (Figure 9). It was felt that this probably reflects the effect of lift provided by warm fronts or in advance of trowals. An examination of weather maps for the years covered in this study reveals a number of cases of widespread hail in advance of warm fronts or trowals, both of which are associated with warm air advection. No definitive conclusion on the effect of the magnitude of warm air advection on the probability of hail

can be drawn, however, because of the small linear correlation coefficients (Table IV) associated with the trend lines.

(ii) Temperatures

As was mentioned in Chapter II, there are a number of ways in which surface and upper-air temperatures should affect the probability of hail. The effect of the temperatures at a number of levels in the atmosphere at Calgary on the probability of hail in the project area was investigated. The resulting trend lines are listed in Table VI.

(a) Maximum Daily Surface Temperature

Figure 10 shows the relationship found between the probability of hail and the maximum surface temperature at Calgary. It was found that the higher the maximum temperature at Calgary the more likely was that day to be a hail-day. This relationship was not well marked in the case of P_1 which was not well fitted to a linear relationship ($r = 0.22$) and had a shallow slope to its trend line. The trend line for the case of P_2 had a slope about twice that for P_1 and quite a high linear correlation coefficient ($r = 0.82$). This difference in slopes is quite reasonable, because more vigorous convection is necessary for a major hail-day than for a minor hail-day, and, in general, increased surface temperature results in increased instability. There seems to be a cutoff temperature below which the atmosphere (as reflected by the maximum surface

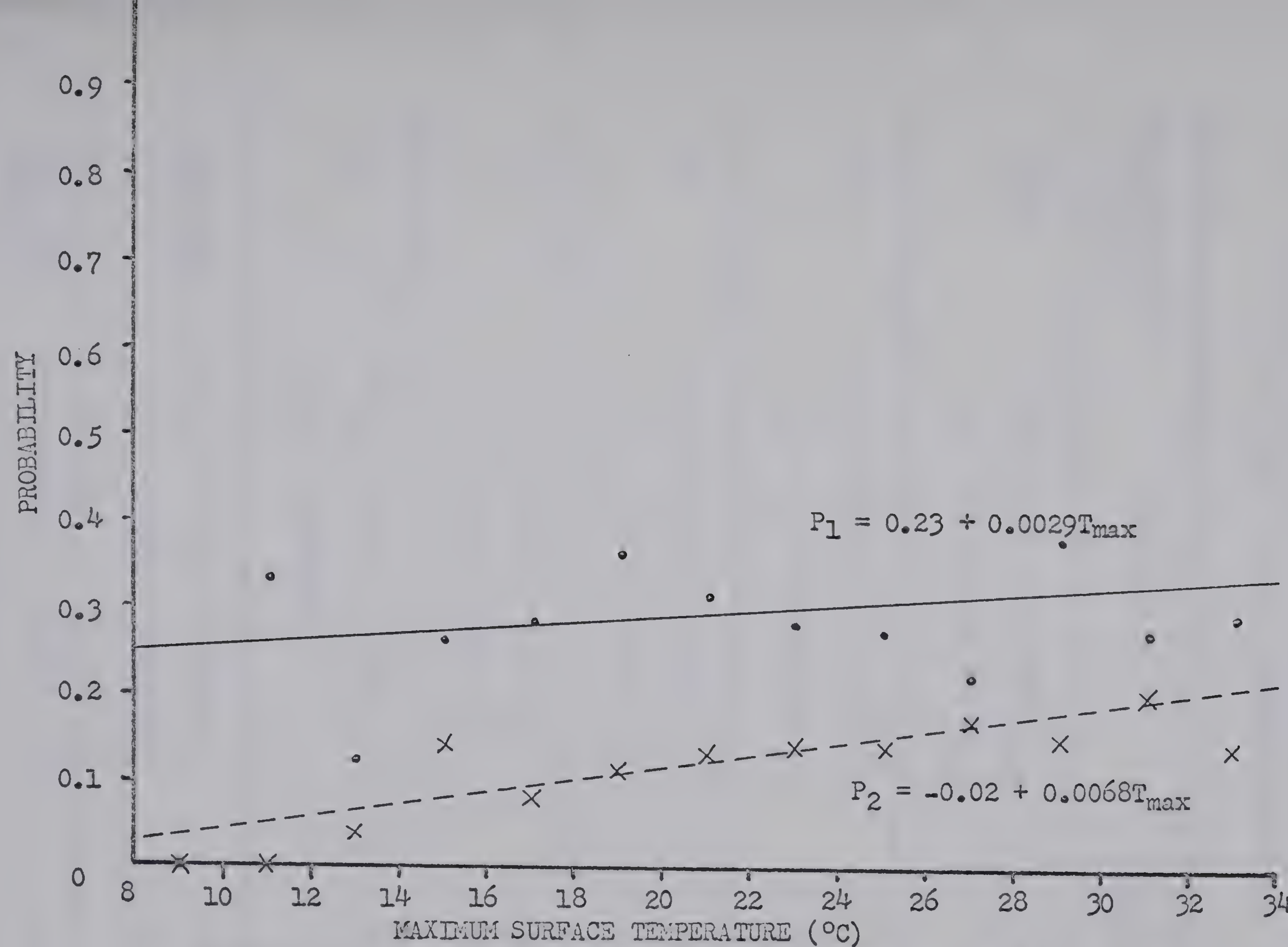


FIGURE 10 - THE EFFECT OF MAXIMUM SURFACE TEMPERATURE ON THE PROBABILITY OF HAIL

TABLE V

TREND LINES FOR THE RELATIONSHIPS BETWEEN UPPER-AIR TEMPERATURES AND THE PROBABILITIES P_1 OF ANY HAIL-DAY AND P_2 OF A MAJOR HAIL-DAY

Temperature Parameter	Trend Line	Correlation Coefficient
T_{max}	$P_1 = 0.23 + 0.0029T_{max}$	0.22
	$P_2 = -0.02 + 0.0068T_{max}$	0.82
T_8	$P_1 = 0.46 - 0.0088T_8$	- 0.52
	$P_2 = 0.14 + 0.00051T_8$	0.04
T_7	$P_1 = 0.33 - 0.011T_7$	- 0.50
	$P_2 = 0.13 + 0.0053T_7$	0.43
T_5	$P_1 = -0.12 - 0.030T_5$	- 0.79
	$P_2 = 0.03 - 0.0073T_5$	- 0.32
T_3	$P_1 = -0.21 - 0.013T_3$	- 0.37
	$P_2 = -0.0035T_3$	- 0.21
Vertical Total dT	$P_1 = -0.19 + 0.016dT$	0.65
	$P_2 = -0.25 + 0.012dT$	0.62
Showalter Index I	$P_1 = 0.34 - 0.048I$	- 0.78
	$P_2 = 0.15 - 0.030I$	- 0.73

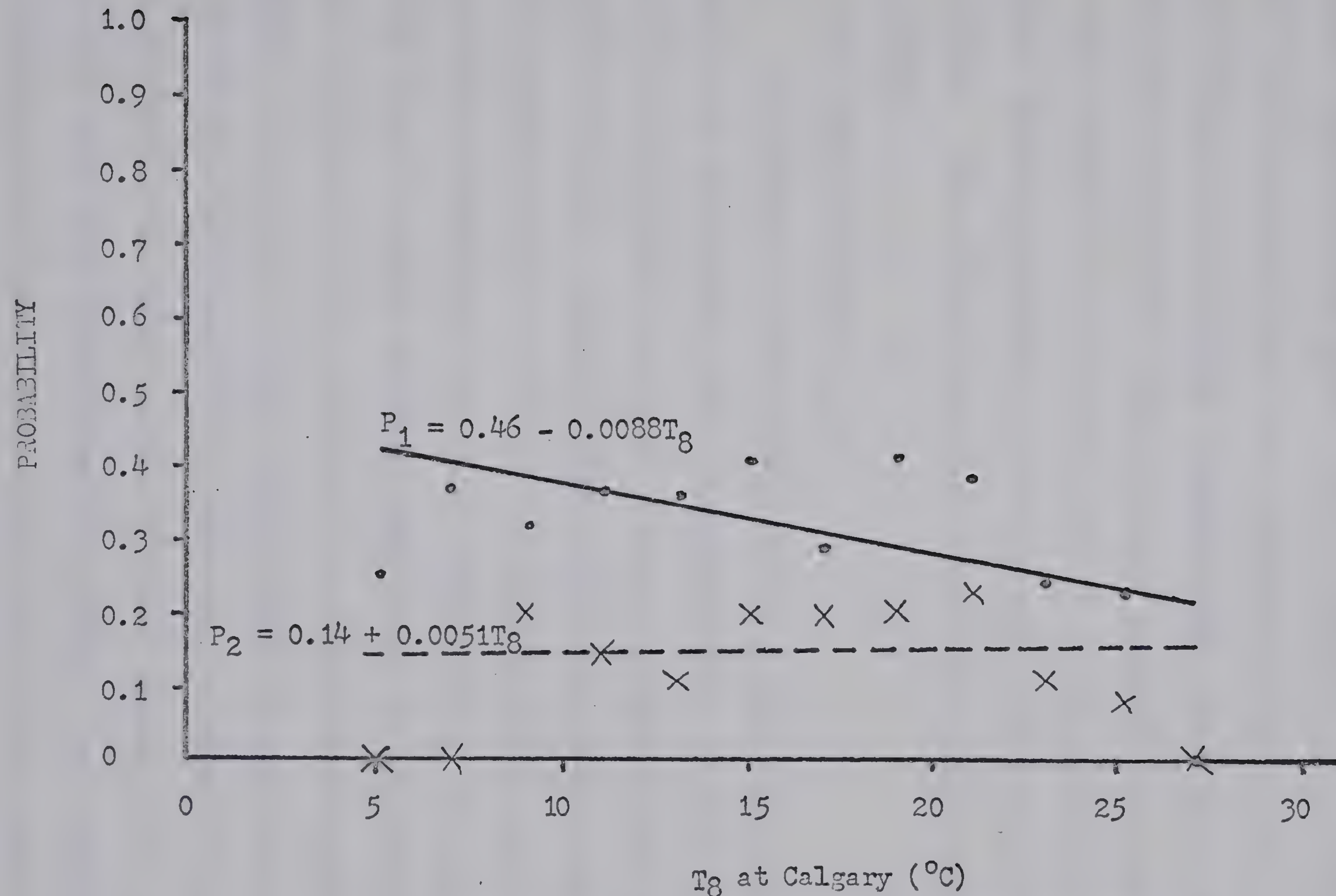


FIGURE 11 - THE RELATIONSHIP BETWEEN THE 850-mb TEMPERATURE AND THE PROBABILITY OF HAIL

temperature) is too cold for sufficient convection to develop to produce a major hail-day. Out of 51 days with maximum temperatures below 14°C only one was a major hail-day. Slight decreases in both P_1 and P_2 were noted for maximum temperatures above 28°C. Although this effect could not really be confirmed because of the small number of days having these maximum temperatures, this is a trend that could be anticipated. High maximum temperatures are indicative of a lack of cloud cover and of the presence of a warm airmass neither of which is associated with widespread hail activity. This effect was also noted by Longley and Thompson (1965).

(b) 850-mb Temperature

In Figure 11 the relationship between the 850-mb temperature at Calgary and the probability of hail is shown. The probability P_1 of a major or minor hail-day was found to decrease slightly with increasing 850-mb temperature, although the scatter of the points about the trend line makes a definite conclusion impossible. The probability P_2 of a major hail-day was found to be insignificantly affected by the value of the 850-mb temperature, although there was a sharp cutoff below 8°C and above 22°C. Out of 27 days with an 850-mb temperature below 8°C there were no major hail-days, and of 54 with temperatures greater than 22°C only five were major hail-days. The cutoff for low temperatures is probably caused by the low amount of

liquid water that a cold atmosphere can hold. Also, cold low-level temperatures are normally reflective of a more stable situation than warmer ones. Melting of hailstones falling through an atmosphere, warm in its lower levels, may be the cause of the high temperature cutoff. It may also be caused by the same effects mentioned in the discussion of the lower hail probabilities associated with high maximum surface temperatures.

(c) 700-mb Temperature

The relationships found between the 700-mb temperature and P_1 and P_2 are shown in Figure 12. P_1 decreased, while P_2 increased, with increasing 700-mb temperature until P_1 was approximately equal to P_2 at a 700-mb temperature of 11°C. The correlation coefficients for both P_1 and P_2 (Table V) were both quite low and thus make the significance of the results questionable. However, the high values of P_1 associated with low 700-mb temperatures may reflect the effect of cooling at this level in increasing the lapse rate and thus promoting instability. P_2 was not high for low temperatures perhaps because of the low liquid water contents associated with low temperatures, a condition unfavorable to the formation of large widespread hail (Longley and Thompson, 1965). These results are essentially in agreement with some of Thompson's (1970) findings. He found that for "swath hail" period in July the mean 700-mb temperature was 3°C, for scattered swath

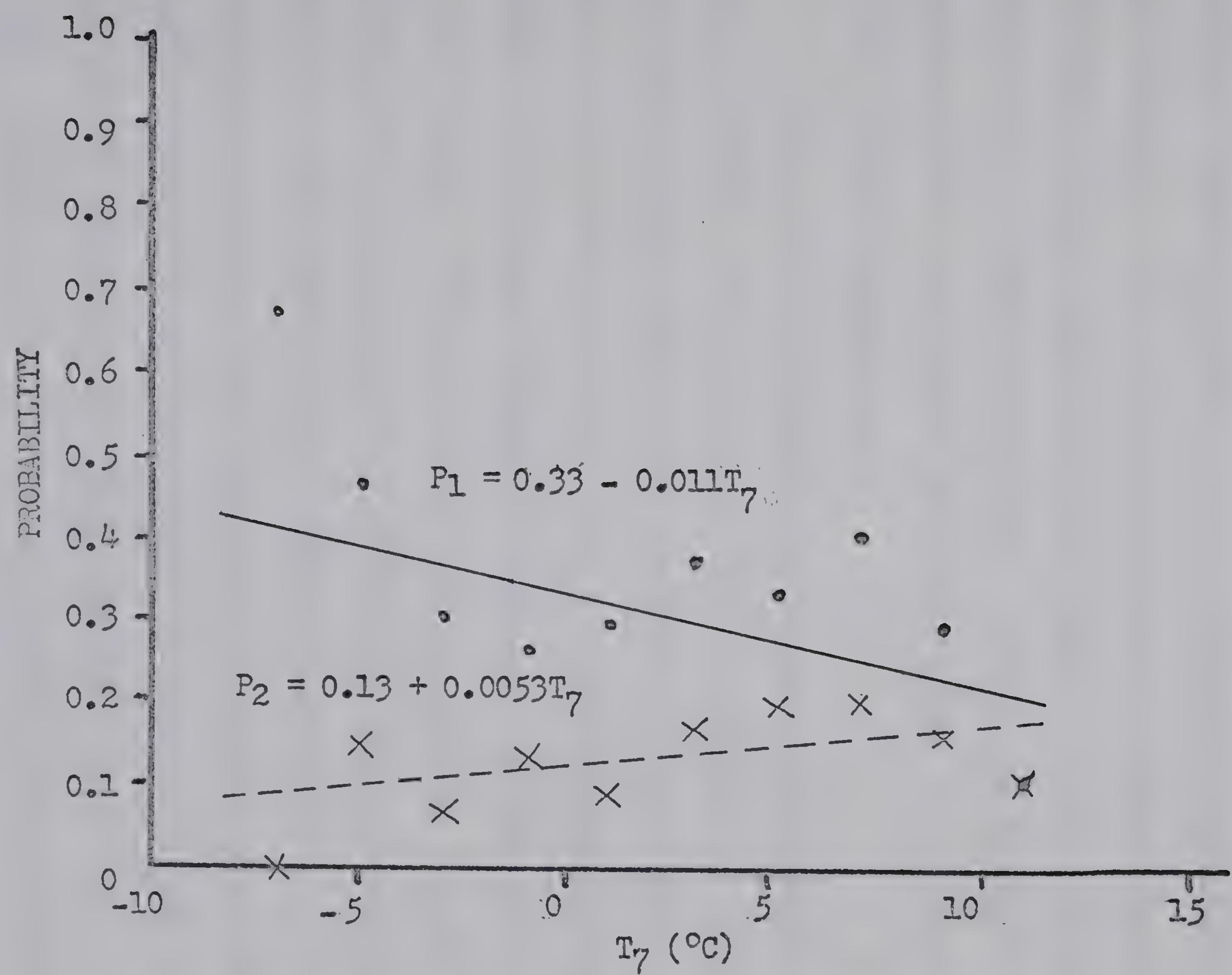


FIGURE 12 - THE RELATIONSHIP BETWEEN T_7 AT CALGARY AND THE PROBABILITY OF HAIL

hail 2°C, for scatter hail 0°C, and for no-hail days 5°C.

(d) 500-mb Temperature

Figure 13 shows the relationships found between the 500-mb temperature at Calgary and the probability of hail in the project area. Both P_1 and P_2 were found to decrease with increasing 500-mb temperature. This was as expected because it had already been mentioned by Longley and Thompson (1965) that cold 500-mb temperatures were favorable to the production of hail. If lower-level temperatures remain unchanged, cooling at higher levels increases the lapse rate and the degree of instability.

(e) 300-mb Temperature

The relationship found between the 300-mb temperature and the probability of hail is shown in Figure 14. This is a trend similar to, although less pronounced than, that which was noted for 500-mb temperatures, and occurs for the same reasons mentioned in the discussion of that level. The slope of the trend line in this case is much less than that for 500-mb because of the smaller temporal variations in the 300-mb temperature. This relationship between cold high-level temperatures and active convection was mentioned by George (1960) and is outlined in Chapter I of this thesis.

(f) Temperature Difference between 850 and 500 mb

A graph of the relationship between the difference in temperature between 850 and 500 mb, the Vertical Totals

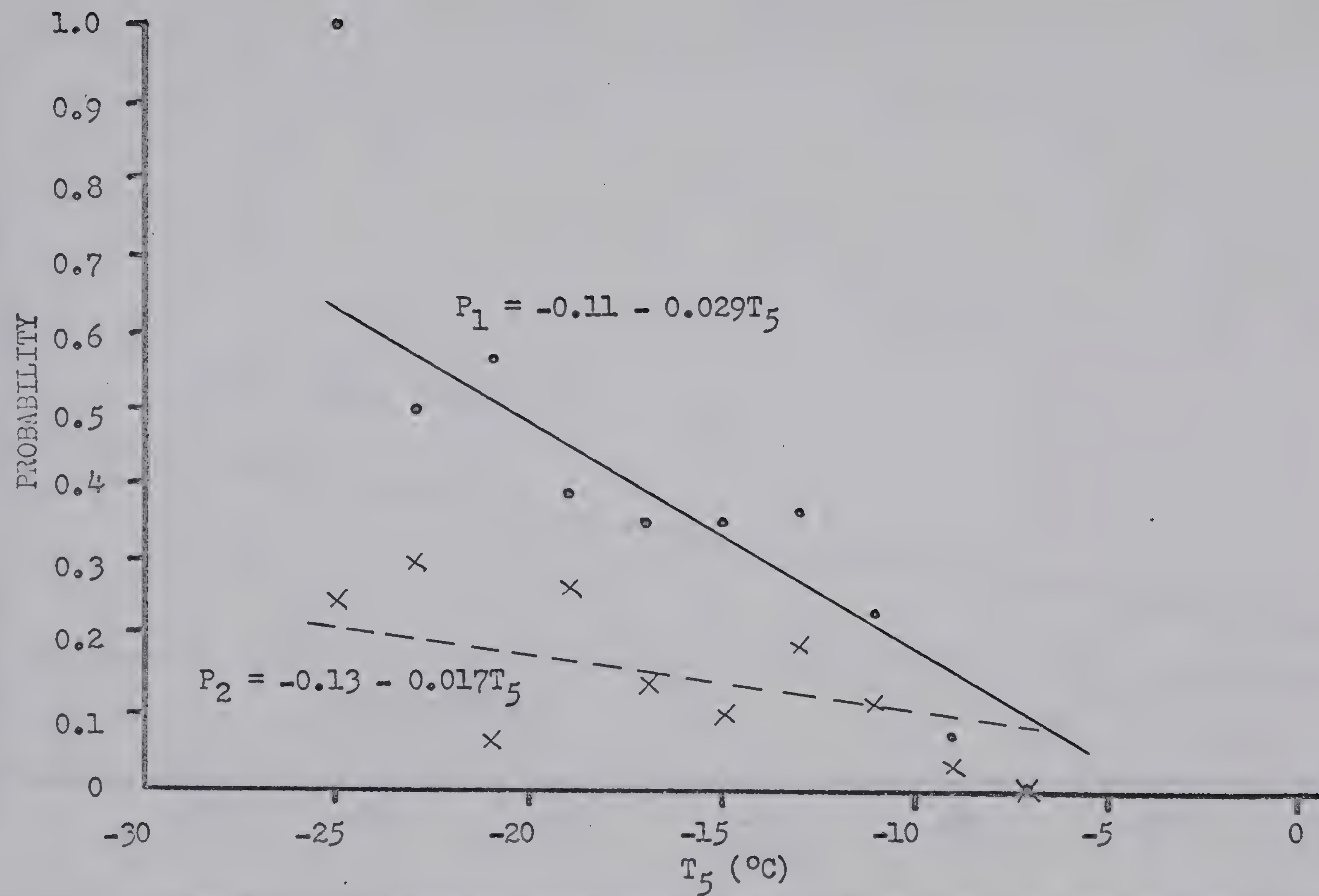


FIGURE 13 - THE RELATIONSHIP BETWEEN T_5 AT CALGARY AND THE PROBABILITY OF HAIL

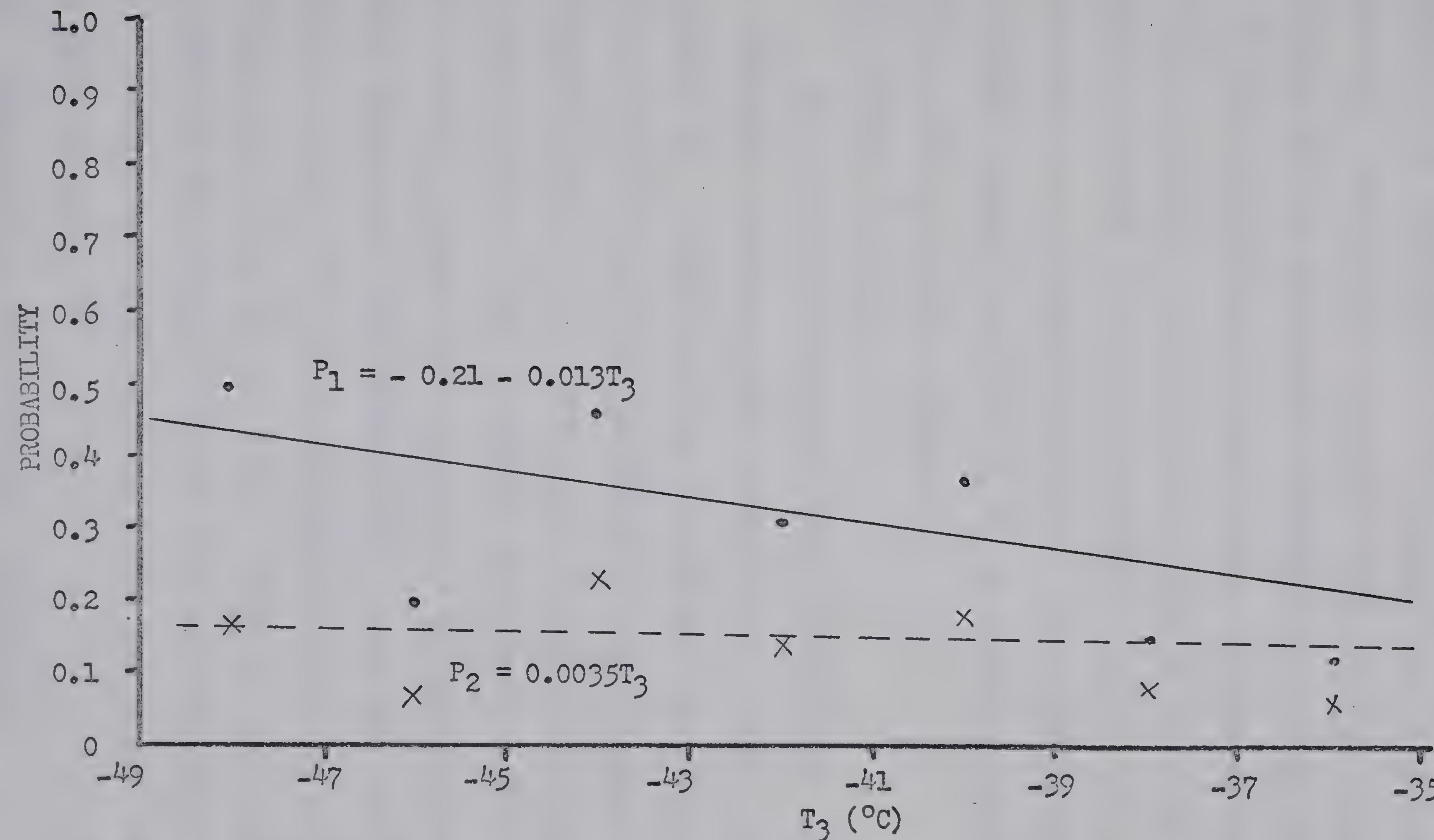


FIGURE 14 - THE RELATIONSHIP BETWEEN T_3 AT CALGARY AND THE PROBABILITY OF HAIL

referred to in Chapter I, and the probability of hail is presented in Figure 15. It was found that the larger the difference in temperature, the larger were the values of P_1 and P_2. This is in agreement with theory, because the magnitude of the temperature difference between 850 and 500 mb is a reflection of the degree of instability present in the atmosphere. The critical value of 26°C for hail-producing clouds, mentioned by Miller (1967), does not look unreasonable on a subjective basis. For values of the Vertical Totals greater than 26° C, P_1 is almost always 0.25 or greater, and P_2, 0.08 or greater.

(g) Showalter Index

The good relationship found between the value of the Showalter Index and the probability of hail is shown in Figure 16. Large negative values of the index were associated with high hail probabilities. Because the Showalter Index is the difference in temperature between the environment at 500 mb and an air parcel lifted from 850 to 500 mb, large negative values are associated with intense convection and instability. When the Showalter Index was below -3°C, hail occurred one day in every two, and major hail, one day in four. Only one major hail-day and only two hail-days occurred with an index greater than +5°C. On only one day when the index was below -4°C did hail fail to fall.

(iii) <u>Combinations of Upper-Air Parameters</u>

The graphs, Figures 17, 18 and 19, in this section

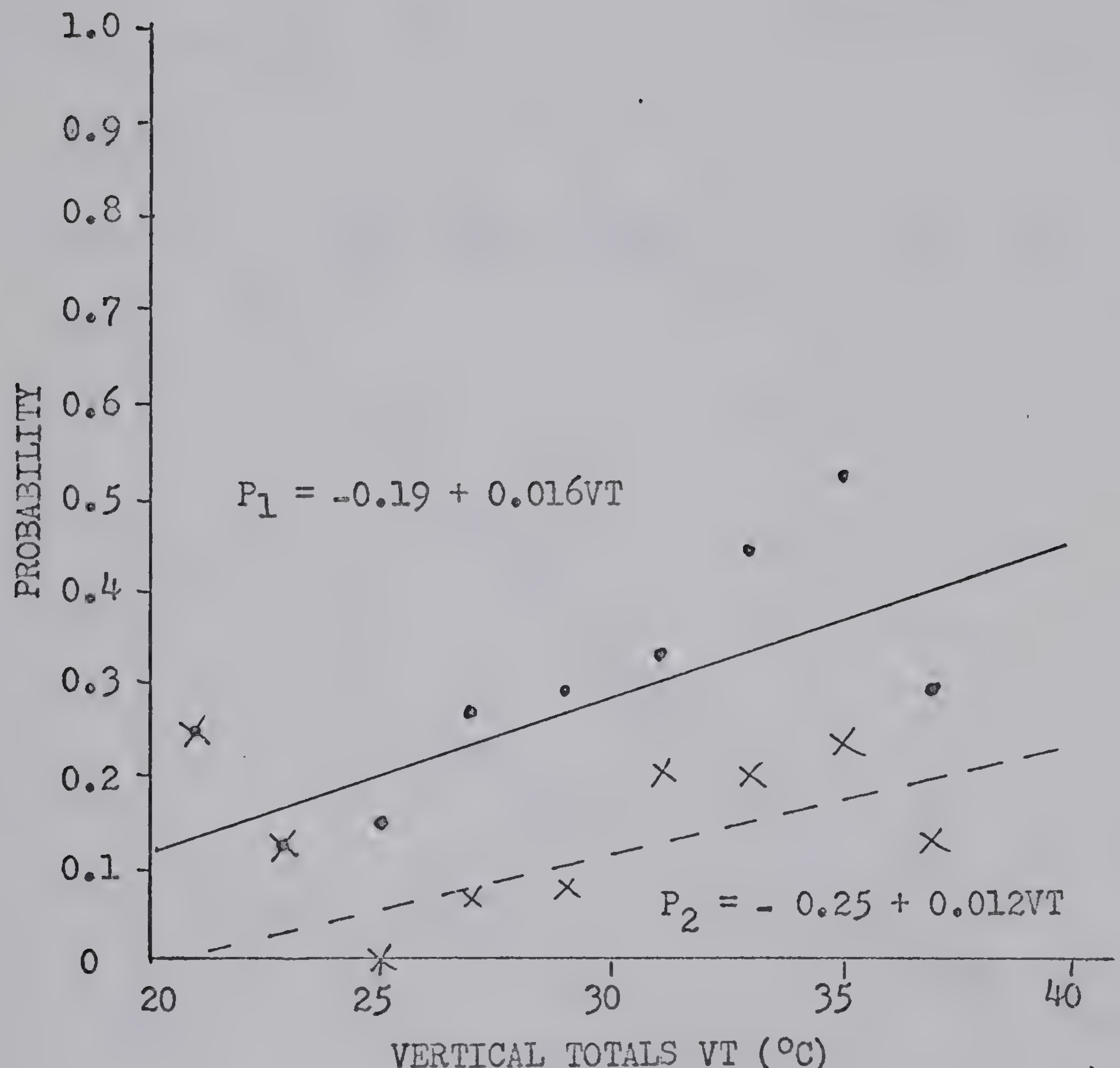


FIGURE 15 - THE RELATIONSHIP BETWEEN VT AND THE PROBABILITY OF HAIL

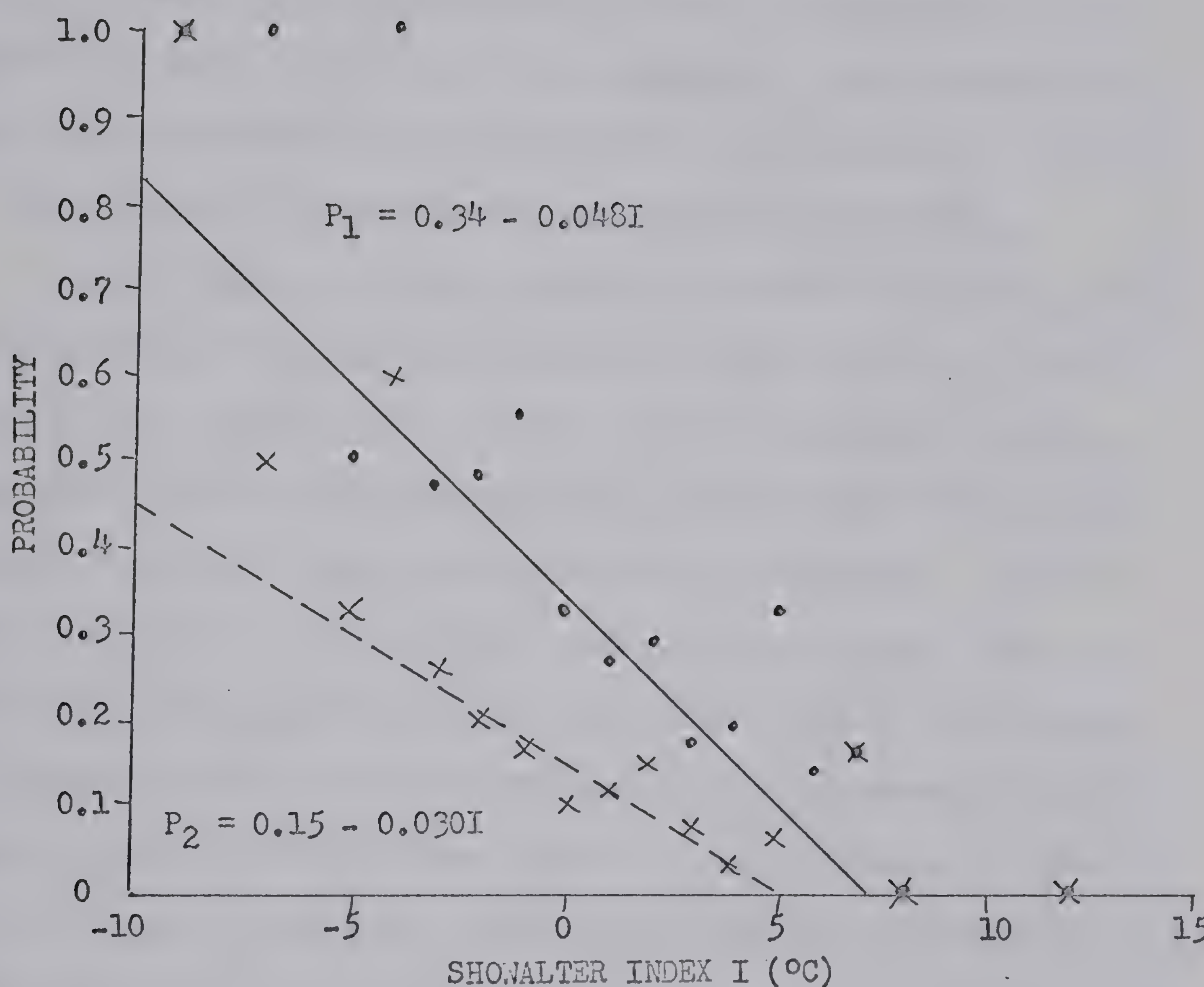


FIGURE 16 - THE RELATIONSHIP BETWEN I AND THE PROBABILITY OF HAIL

were drawn using the following codes:

Solid lines - isopleths of $P_1 = 0.20$ and 0.50

Dashed lines - isopleths of $P_2 = 0.20$ and 0.50

In drawing the isopleths, the reliability of the probability values was subjectively weighted depending on the number of days included in the samples. This number of days is indicated in each square of the graphs.

(a) Surface Temperature and Relative Humidity

In Figure 17, the effect of surface moisture, as reflected by the surface temperature and relative humidity, on the probability of hail is illustrated. As was expected, the highest probability of hail was found to be associated with high surface moisture contents. P_2 was 0.20 or greater for relative humidities greater than 50 per cent and temperatures greater than 20°C. This range of temperatures and relative humidities represents about one-sixth of all days considered. The presence of low-level moisture has long been recognized as a contributing factor to convective development (Sly, 1965, 1966 and 1967, and others).

(b) 850-mb Temperature and Relative Humidity

Figure 18 illustrates the effect of the atmospheric moisture content at 850 mb on the probability of hail. Maximum hail probability was found to occur when temperatures and relative humidities were high, a similar result to that obtained when the surface temperature and relative humidity were considered. P_1 was greater than 0.20 for

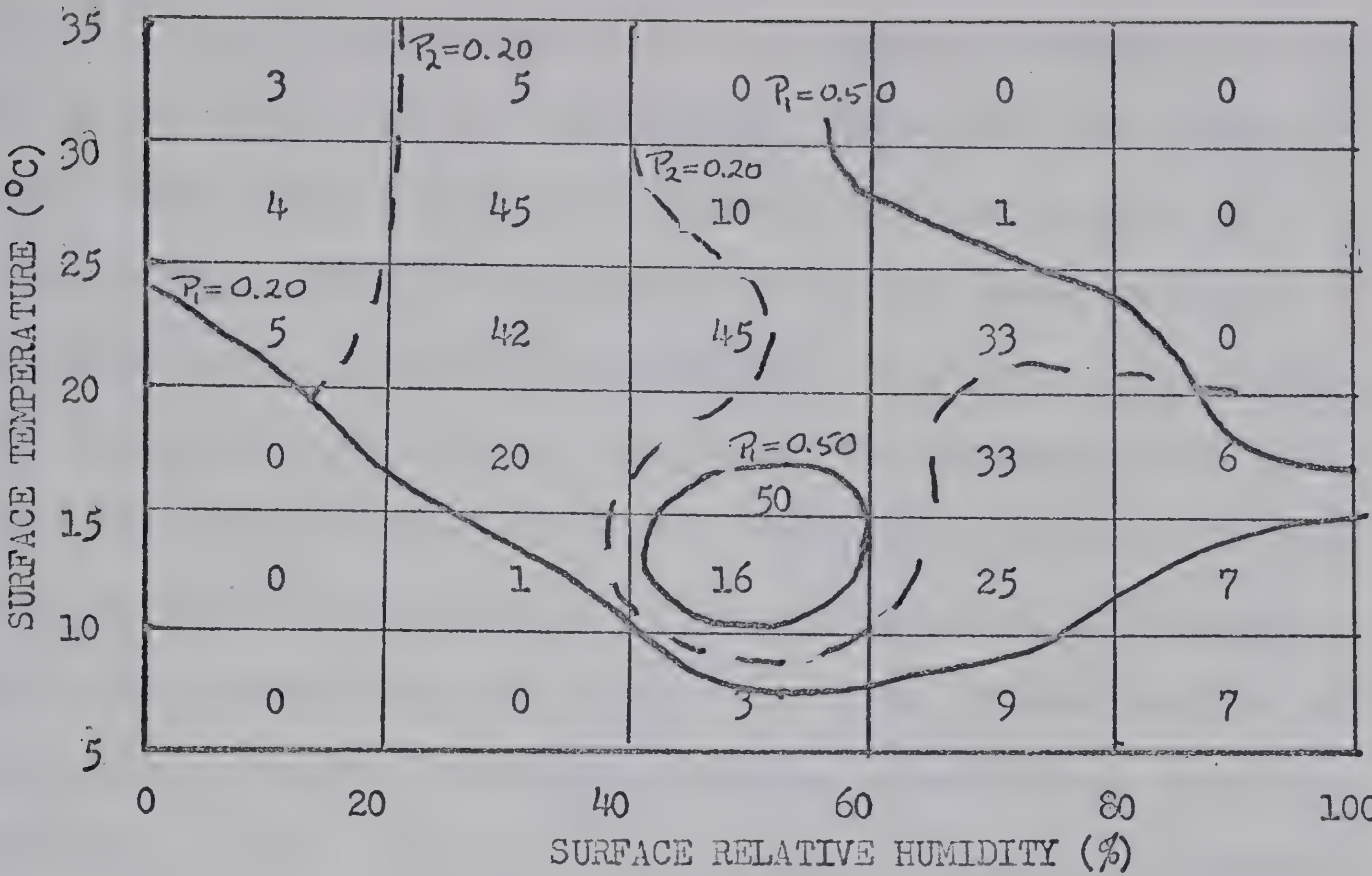


FIGURE 17 - RELATIONSHIP BETWEEN SURFACE MOISTURE AND THE PROBABILITY OF HAIL

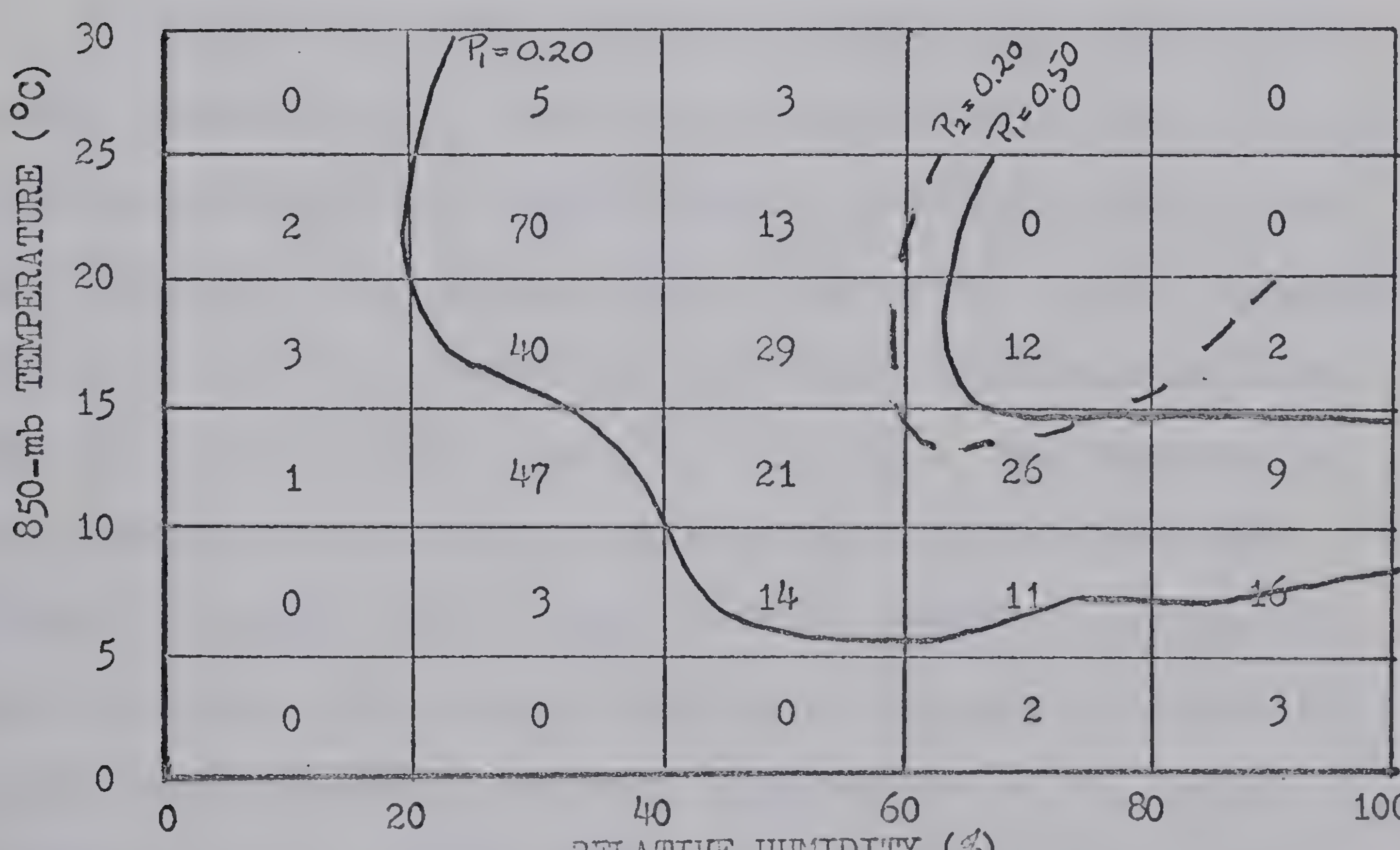


FIGURE 18 - THE RELATIONSHIP BETWEEN 850-MB MOISTURE AND THE PROBABILITY OF HAIL

850-mb temperatures above 5°C and relative humidities in excess of 20 per cent, and greater than 0.50 for temperatures above 15°C and relative humidities in excess of 60 per cent. This is as expected for the same reasons outlined in the previous paragraph. In Figure 11, which was discussed earlier, P_1 was shown to decrease with increasing temperature. However, the points between 18 and 20°C in this figure show that the probability is higher than the values given by the trend line. These points are probably associated with days having high 850-mb moisture contents as is indicated by the area in Figure 18 between 15 and 29°C and 60 and 100 per cent.

(c) Thermal Wind between 850 and 300 mb and the Vertical Totals

Figure 19 illustrates the effect that was found on the probability of hail of the magnitude of the thermal wind between 850 and 300 mb and the Vertical Totals. It was found that the probability of any hail day was greater than 0.20 when the Vertical Totals was greater than 28°C and the thermal wind less than 44 m/sec. The probability of a major hail day was greater than 0.20 for Vertical Totals in excess of 32°C and thermal winds of between 16 and 36 m/sec. The area of the graph between 32 and 36°C and 20 and 38 m/sec. has very high values of P_1 and P_2. In this area, P_1 ranged from 0.53 to 0.90, and P_2, from 0.20 to 0.50. The overall distribution of the hail probabilities seemed to indicate a greater dependence on the

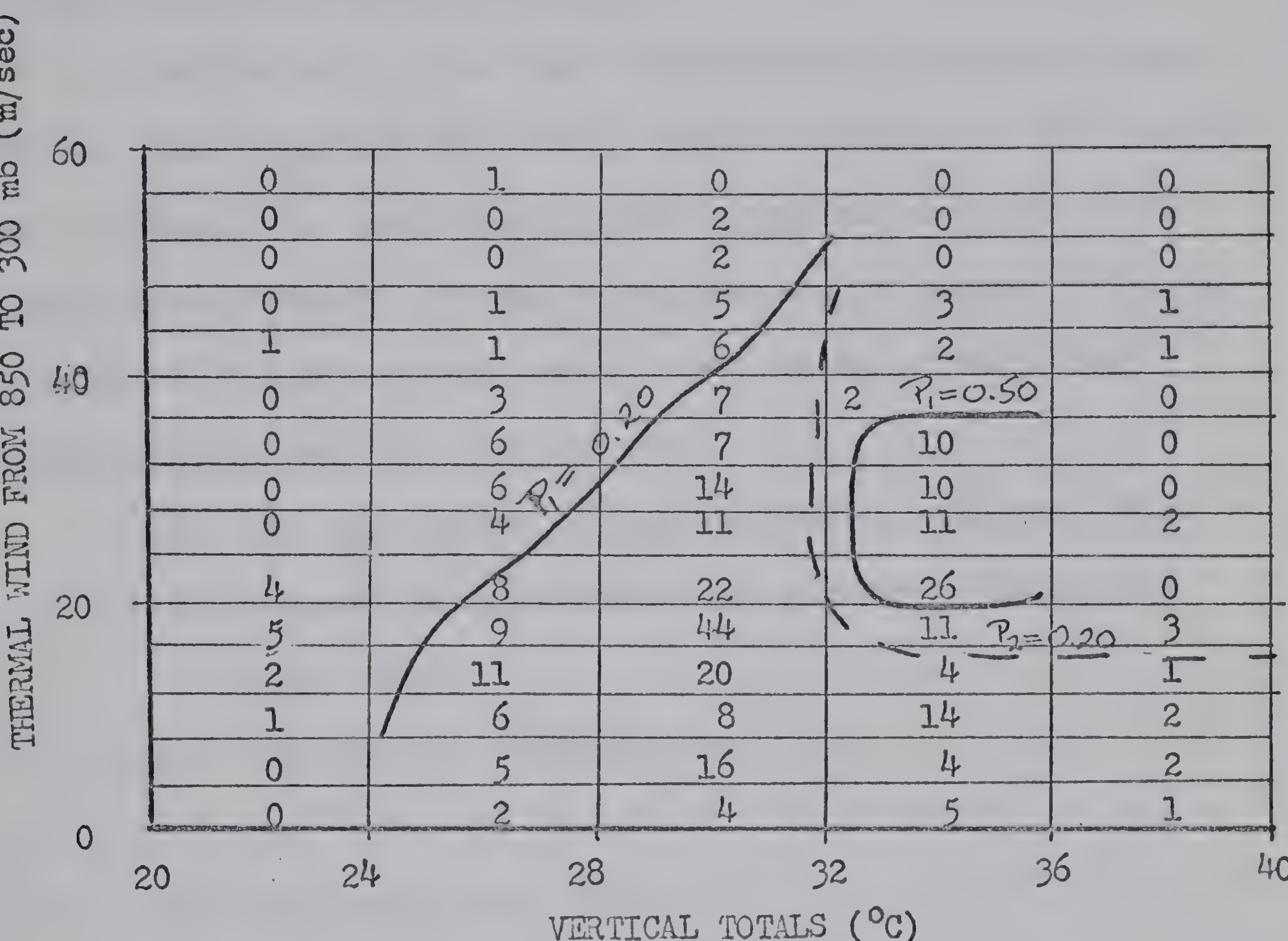


FIGURE 19 - THE RELATIONSHIP BETWEEN THE THERMAL WIND FROM 850 TO 300 mb, THE VERTICAL TOTALS, AND THE PROBABILITY OF HAIL

Vertical Totals than on the wind shear, although a shear value of 44 m/sec. seemed to delineate the top boundary of hail occurrence on the graph.

The Calgary upper-air parameters that were examined in this chapter for their relationships to the occurrence of hail in the Alberta Hail Studies project area varied considerably in the significance of their effects. Quite good relationships were found between hail-day probabilities and the following:

i) The direction of 850 to 300-mb Thermal Wind

ii) The maximum surface temperature (for major hail-days)

iii) The 500-mb temperature

iv) The Vertical Totals

v) The Showalter Index

vi) The surface moisture content

vii) The 850-mb moisture content

viii) The Vertical Totals and the 850 to 300-mb thermal wind

CHAPTER VI

CONCLUSIONS

It was felt that the hail data used in this study were of sufficient density and accuracy to classify days as major, minor, or no-hail. Radiosonde data were available from Edmonton and Calgary. Initially, a relationship was sought between the various upper air parameters at Edmonton and hail occurrence in the northern part of the hail studies area, and parameters at Calgary and hail in the southern part of the area. For the reasons mentioned in Chapter IV, it was felt that there was little to be gained by considering hail probability in the two separate areas. Thus, the main analysis attempted to relate hail probability in the entire project area to values of the upper-air parameters at Calgary.

A hail index was proposed that takes into account the size distribution of hail on a particular day. This type of index seems preferable to one that considers only the number of hail reports because of the importance of hail size in determining the severity of a hail day.

It was found that when there was a northerly 850-mb wind at Calgary, hail occurred in the southern area (Figure 3) two days out of every five, while, when there

was a southerly wind, hail occurred one day in five. The direction of the 850-mb wind at Edmonton had a negligible effect on the probability of hail in the northern area. When the 850 to 300-mb thermal wind at Calgary was from the south, hail occurred in the southern area two days out of every five, while with northerly thermal wind hail occurred one day out of every ten. A southerly thermal wind at Edmonton was associated with hail one day in three, and a northerly one, one day in twenty.

A number of good relationships were found between Calgary upper-air data and hailfall in the entire project area. Particularly marked relationships were found between the two stability indices considered and the probability of a hail-day. The probability of a major or minor hail-day was generally 0.20 or less when the Showalter Index exceeded 3°C, and, 0.50 or more, when the index was less than -3°C. Major hail-days occurred on at least one day in four when the index was below -3°C. These results are in general agreement with Showalter's (1953) critical index values listed in Table I. There was also a pronounced relationship between hail-day probability and the vertical totals index. For vertical totals in excess of 26°C the probability of a hail-day was always 0.25 or greater. Thus, Miller's (1967) critical vertical totals value of 26°C for thunderstorm activity does not seem unreasonable for use in Alberta.

The magnitude of the 850 to 300-mb thermal wind had little effect on the probability of hail, a result similar to Proppe's (1965) findings. There did, however, appear to be a slight increase in hail-day probability with increasing thermal wind speed between values of 20 and 40 m/sec, and a dropoff in hail-day probability for speeds in excess of 40 m/sec. This result tends to confirm Dessen's (1960) results that were listed in Chapter III of this thesis. Thompson (1970) found that hail patterns in the presence of strong upper-level winds did tend to be organized in the form of swaths. He did, however, conclude that the presence of strong upper-level winds was not a necessary condition for swath hail.

The probability of hail was found to be quite well correlated with the direction of the 850 to 300-mb thermal wind, ranging from 0.28 for a northerly direction to 0.43 for a southerly one. However, the magnitude of the net thermal advection in the 850 to 300-mb layer was found to have little discernible effect on the probability of hail. The only conclusion that could be drawn was that, in general, hail was much more likely in cold air advection situations than in warm ones.

Cold 500-mb temperatures were found to be correlated with high hail-day probabilities. The probability of any hail-day ranged from 0.61 for a temperature of -25°C to 0.09 for a temperature of -7°C, while for a major hail-day

the probability ranged from 0.21 to 0.09 over the same temperature range. Although Thompson's (1970) results are not directly comparable to those in this thesis because of the different type of hail-day classification that he used, it was felt that his swath hail-days would almost all be major hail-days as defined in this thesis. He found that the mean 500-mb temperature on swath hail-days was -14°C, a result comparable to that illustrated in Figure 13 of this thesis.

Finally, in agreement with most previous investigators in this field, the presence of high moisture contents in the lower atmospheric levels (surface and 850-mb levels in this study) were found to be associated with high probabilities of hail.

Some of the parameters investigated in this study were found to be well enough related to the probability of hail to warrant testing on an operational basis. Using the large variety of computer-produced prognostic charts now available it should be possible to make forecasts of most of the parameters considered in this thesis. By associating the appropriate hail probability values with the parameters it should be possible to delineate areas most likely to experience hailstorm activity.

There is room for considerably more research along the lines begun in this study. With the recently initiated summer radiosondes at Penhold (begun in 1967) and at Rocky

Mountain House, Alberta (begun in 1969) it should be possible, once a sufficient period of record has been obtained, to undertake a more detailed study than has been possible in this thesis. With two radiosondes in the main hailstorm area (the Calgary radiosonde having apparently been discontinued), it should be possible to obtain relationships between upper-air data from them and hail probability in the areas adjoining the two sites.

Of course, as more hail and upper-air data become available in future years, it will be possible to be more certain of the accuracy of any predictors of hail. An increase in the density of the networks of hail observers and radiosondes is desirable, but will probably not be possible until economically more practicable.

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